THE ELECTRIC RAILWAY

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PREFACE

For several years the author has felt the need of an adequate text-book for instruction of advanced students taking electric railway courses. It was to meet this need that this volume was prepared. It is so arranged that certain portions may be omitted without affecting the continuity, as each chapter is a complete unit in itself.

Since most students take electric railway courses after having mechanics, a fundamental knowledge of this subject is assumed. Similarly, power plant and transmission line work are usually taken as independent courses, and are referred to in this book only as they directly affect the main subject. Car house design and equipment are entirely omitted, for, while of prime importance in electric railway operation, they are topics of limited scope which have no direct bearing on the other factors which make up a railway system. Such points are very fully covered in some of the recent electrical handbooks.

Although intended primarily as a text-book, it is believed that this volume contains much matter of interest to the practising engineer, since it purposes to give the underlying principles of electric railway design and operation. It must, however, be borne in mind that no attempt has been made to write a handbook, and that definite figures have been given only when necessary to make the text clear.

In connection with a book of this character, the author considers it essential that frequent reference be made to the current technical press for standard practice and recent developments in the field. The *Electric Railway Journal* is especially to be recommended in this connection.

It is impossible to give credit for all the suggestions and criticisms which have aided the author in the preparation of this book. The sources of material are given, so far as possible, in footnotes. Especial thanks are due Prof. A. S. Richey, of Worcester Polytechnic Institute, for reading the manuscript, and for valuable suggestions made by him; and Mr. E. G. Young, of the University of Illinois, for his aid in preparing the illustrations.

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A. M. B.

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CHAPTER I

INTRODUCTION

The Requirements of Transportation.—The problem of transportation is one of the greatest in engineering; in many respects it is the most potent factor in our modern civilization. When communities were small and self-contained, there was little need for other than local service. As soon as it was found that a community could produce more of a commodity than was needed for local consumption, while at the same time it lacked in other necessities, an interchange of such products was found desirable and even necessary. With this traffic came a need for passenger transportation, since agents were required to attend to the necessary transactions due to the traffic developed.

Ever since the beginning of history this interchange of merchandise has been one of the great vocations of mankind. Until about the beginning of the nineteenth century the traffic on land was handled exclusively by animal power. As the result of experiments made by a number of investigators in the first portion of the last century, mechanical means of transportation were made available. The motive power thus invented was the steam engine, which was developed into the prototype of its modern form when Stephenson's "Rocket" was built in 1829. The results attained as the outcome of this invention were far-reaching; it entirely revolutionized all methods of transportation.

The problems involved in railway service are many and varied. Although transportation is one of the earliest activities of mankind, the modern railroad really had its beginning with the use of steam as a motive power, in the early part of the nineteenth century. From humble beginnings, it soon developed along two radically different lines: the main-line or "trunk" railroad, and the street railway or "tramway."

The Trunk Line Railroad.—This is usually considered to be a line of considerable length, handling traffic in large units and at moderate or high speeds. In most cases the trunk railway has been built to meet the demand for a transfer of commodities from point of production to point of consumption, and incidentally to handle the passenger traffic originating in its territory. Such a road is one connecting a number of cities of large size, and handling all classes of freight and passenger service. On this type of railway the freight business is usually of greater importance than the passenger, the latter often being handled merely as a necessary incident to operation.

The Street Railway.—The street railway has been developed along radically different lines, and is a direct result of the growth of communities. At the beginning of the nineteenth century, the area of the largest of cities was sufficiently small that practically all residents could have their homes within reasonable walking distance of their work. As towns grew larger, more rapid means of transportation became imperative to prevent unnecessary waste of time in going to and from business. The earliest solution of the problem was the use of the omnibus, which increased slightly the radius within which a worker could choose his home. From this to the "tram-car" or horse-car was a short step, the difference consisting merely in adapting the omnibus to run on a track laid in the city streets. The horse railway was developed for about 50 years, reaching its zenith in the early eighties. The possible increase of schedule speed, depending as it did on the physical capacity of the horse, reached its maximum soon after the introduction of this type of motive power. This limitation became so serious that mechanical devices were sought to increase the possibilities of the street railway. Steam, gasoline, compressed air and the cable were all tried, with varying degrees of success.

The Cable Railway.—Of these motive powers, the cable was the only one that gave anything like satisfactory service. Introduced in 1873, a number of cable lines were installed in the succeeding 20 years, and operated with varying degrees of success. The salient feature of this system was a wire rope, driven by a steam engine, and running the entire length of the track in a slotted conduit of concrete and iron, located between the running rails. Power was transmitted to the car by mechanical clutches or "grips" fastened to the car body, and extending

into the conduit to engage the cable. Starting the car consisted in clutching the cable with the grip, and in that way obtaining the necessary force to move the train. It is evident that only one speed was possible; and, due to the constructional features of the system, the velocity was limited to about 10 miles per hr. The starting conditions were also bad. Either the train would start with a jerk, or else the grip would slide along the cable before catching hold of it, causing excessive wear. Cables of the size used were expensive, and were subject to frequent breaks, necessitating complete shut-downs of the system during repairs. On account of the design, the cost of construction was almost prohibitive, being over $100,000 per mile of track. Only the most densely populated cities could furnish sufficient traffic to warrant the installation of the system.

The Electric Street Railway.—In 1884 the first practical electric railway in the United States was put in operation at Cleveland, Ohio, by Edward M. Bentley and Walter H. Knight. Almost immediately afterward a number of other electric roads commenced running; and it became apparent at once that the use of electricity furnished a satisfactory solution of the problem of giving rapid transit to cities. Its application spread quickly, until today it is the only power considered for this class of service. It has also replaced all the other methods of operation which have been tried from time to time; and has permitted of extensions and forms of service out of the question with other motive powers.

The Interurban Railway.—In connection with many city railway systems, it was found possible to develop a profitable suburban passenger business, usually serving city workers who desired to live in the country, and were willing to spend a little more time in traveling than the ordinary city resident. In many cases this brought the electric roads into active competition with parallel steam roads. Almost without exception the former were able to handle this class of traffic better than their competitors, so that today the steam roads have been practically driven out of the suburban business.

The success of suburban roads encouraged promoters to venture further into the steam railway field by building lines between centers of business for the handling of passenger traffic. These interurban railways have usually been successful, since their relations with the city lines have enabled them to give

better service than the steam roads, even though their schedule speeds are ordinarily lower. These roads have developed an entirely new class of business—a passenger traffic between the rural districts and the cities. Farmers have found it easier to use the electric passenger cars than to drive their teams to the towns. As a consequence they travel much more than they formerly did. This rural traffic has in turn caused a demand for an express and package freight service on the interurban lines. Such business is usually quite profitable to the railways, being handled by the regular passenger trains with little extra cost. In some few cases, the growth of this business has been so great that it has been found impossible to accommodate it with the passenger equipment; and regular freight and express trains are operated entirely apart from the passenger business.

Scope of the Electric Railway.—During its 30 years of successful development, the scope of the electric railway has broadened materially. Not content with city operation alone, the managers of city roads have, as just stated, extended them to embrace suburban and interurban passenger service. These latter developments were not made without opposition from the established steam lines with which they competed; but within the past few years the steam railways have realized the possibilities of utilizing electric power on their own systems for serving the same class of traffic.

At the present time the use of electricity for the hauling of freight is quite limited, and by far the larger number of electric roads are equipped for the handling of passenger trains exclusively. Electric freight service is, however, expanding rapidly, and it will not be surprising to find many railroads using electric power for this purpose within the next decade.

Many steam roads have seriously considered the use of electricity on certain divisions, and several have already made the change. The operation of such lines as have been electrically equipped has been so highly satisfactory as to warrant the further extension of the system in practically all cases. By this it must not be understood that electric power is a universal panacea, as has been assumed by some persons; but that, when correctly applied and intelligently used, it may effect certain operating economies which will make it desirable.

Classification of Railways.—For purposes of study, railways may be divided roughly into three main groups:

1. Street railways ("tramways").
2. Suburban and interurban railways.
3. Trunk-line railways.

The first group consists of roads with light rolling stock, the operation of which involves many stops and low schedule speeds. Since the distance covered by a car in a given time is proportional to the schedule speed, it is necessary to bring it from rest to a fairly high velocity in a short time, and to stop it quickly. Such a run demands high rates of acceleration. This class of road is exclusively for passenger service.

The second group comprises roads using considerably heavier rolling stock than the first, with fewer stops and at higher speeds. On account of the smaller number of stops the demands on the motive power are not so severe as in the first class. Many roads in this group handle express and light freight, some of them obtaining a considerable share of the total revenue from these sources.

The third group is made up of the heaviest classes of service, involving both passenger and freight business. The passenger runs are in general of considerable length and at high speeds. On such roads the suburban and local passenger business, although appearing a large item to the casual observer, is a comparatively small portion of the total. The net earnings depend almost entirely on the handling of heavy freight.

The above classification of railways is by no means absolute. A considerable number of suburban roads will fall between the first and the second groups, the cars being either the same as those for city lines, or slightly heavier, and operating from the center of a city into its suburbs. Similarly, a number of interurban roads approach very nearly to the third group, although their rolling stock and schedules do not justify classification with it. Elevated and subway service is in general a compromise between the first and the second groups, although not belonging to either; for it combines the requirements of a considerable number of stops and a high schedule speed. The rolling stock is moreover of such a weight as to justify its classification in the second group.

Motive Powers. The Steam Locomotive.—For railway service, a number of different motive powers have been suggested, and some of them actually used. A brief description of them will aid in understanding the conditions in the motive power field, and the place the electric system has in it.

The steam locomotive has excellent characteristics for heavy railway service. It is unique among motive powers in that it comprises in itself a complete steam power plant. The capacity of a locomotive depends on two main factors: the size of the boiler and the size of the cylinders. At slow speeds, the tractive effort is produced by the maximum pressure of the steam against the piston. This maximum pressure may be maintained practically constant so long as the boiler is able to supply steam

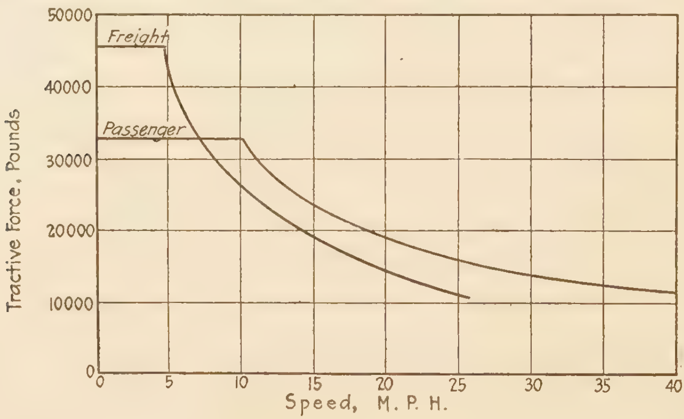


FIG. 1.—Characteristics of typical steam locomotives.

to the cylinders. Since the number of strokes, and hence the quantity of steam used, varies directly with the speed, a point must be reached where the boiler cannot keep up its pressure against the increasing demand for steam. To reach higher speeds the cut-off must be advanced, so that the amount of steam taken *per stroke* is reduced. The higher the speed, the earlier must be the cut-off, and hence the less the mean effective pressure and the tractive effort. This is shown graphically in Fig. 1, which gives a tractive effort–speed curve of a modern passenger engine and of a modern freight engine. In the high-speed portion of the curve the locomotive is virtually a constant power machine, since the tractive effort varies almost inversely as the speed.

The performance of the cylinders is hampered, since they rely for their steam on a boiler of limited capacity. The boiler in turn is dependent on the fire-box and the ability of the fireman to keep it properly supplied with fuel. Owing to the necessity of getting maximum capacity per unit of weight, the performance is forced beyond the most efficient operating point. The draft is so great that a large portion of the fuel (in case coal is used) is thrown out of the stack in the form of cinders. Tests show that approximately one-tenth of the total weight of coal fired is discharged in this manner. Although it may be possible, by the use of special precautions, to operate the steam locomotive without smoke or dirt, it is in general impractical to do so. Since the entire power plant, and also a supply of fuel and water, must be hauled in addition to the train, there is a distinct loss of efficiency due to that cause.

The steam locomotive is most efficient when built in the larger sizes, since many of the losses are nearly constant, or increase more slowly than in proportion to the weight. The limit is reached only by the ability of the fireman to handle the necessary amount of coal. In some recent locomotives mechanical stokers are used, resulting in some increase in capacity over hand firing. In the smallest sizes, the steam locomotive is decidedly inefficient, and in many respects is not the excellent machine that has been developed by the designers of modern large engines.

Other Motive Powers.—Gasoline and other fuel oils have been used in connection with internal combustion engines. While these combinations are, in common with the steam locomotive, complete power plants, they are considerably simpler, and are lighter than it per unit of output. They also operate with but a small fraction of the smoke and dirt incident to the steam locomotive. The internal combustion motor is inherently a constant-speed machine, and special means must be employed to reduce speeds at starting and for slow running. In the automobile this is brought about by changes of gearing, and variations in the amount of charge and the time of its ignition. At best these methods give an imperfect speed control; and they are not very practical for heavy train service.

Compressed air and stored steam have also been tried for motive powers. The engines are similar to the ordinary locomotive steam engine, but are supplied from tanks on the loco-

motive containing either steam or air compressed to a high pressure. Owing to the high storage capacity necessary, and to the low thermodynamic efficiency of the complete cycle, they have not been successful. A few locomotives of these types are used in mines, where the fire of the steam locomotive would be liable to cause explosions of the mine gases.

The cable has already been mentioned. It was never suited to any class of service except in congested city districts, and even there its limitations forced its retirement as soon as a better motive power was available. At the present time the only roads operated by cable are in a few places where the grades are so steep that some form of positive drive is necessary.

Electric Systems.—For railway service, there is available a number of combinations of motors and electric circuits, giving an almost unlimited flexibility, and enabling the engineer to choose the best type of equipment for each case. In fact, this wide range of choice is one of the factors which has prevented earlier consideration of electrification by steam railroad managers, who are to a certain extent awaiting the standardization of one or another of the principal systems of electric operation.

Although practically every type of electric motor ever built has been used or suggested for traction at one time or another, there are in use three systems which have driven out all others for practical service:

1. The direct-current system, using series-wound motors.
2. The single-phase alternating-current system, using
   (*a*) Single-phase commutator motors, or
   (*b*) Three-phase induction motors operated through a "split-phase converter."
3. The three-phase alternating-current system, using three-phase induction motors.

It is beyond the scope of the present chapter to present an extended discussion and comparison of the different electric systems. They will be taken up part by part in later chapters, with a summary under "Systems of Electrification." In general, the direct-current series motor and some of the alternating-current commutator motors possess characteristics quite similar to those of the steam locomotive engine, with even better performance at starting; while the induction motors operate at substantially constant speed throughout their working range. The speed of each type may be reduced for starting or slow run-

ning by purely electrical means, thus obviating the necessity of change gears, as with the internal combustion engines. The efficiency of each is high, and, including all losses in generation and distribution, is at least as good as that of the steam locomotive.

Of the three systems, the direct-current has been in use the longest time. All of the early experiments were made with direct-current motors; and for about 20 years alternating current was not even thought of in connection with railway operation. It is evident that the direct-current motor, having passed through a long stage of experimentation and development, has reached the highest state of perfection at the present time. All railways of the first class (street railways) are operated by this system; and in this kind of service it has proved eminently satisfactory. Whether it will maintain its excellent reputation in the heavier classes of traction remains to be proved.

Advantages of Electric Systems.—As compared with other motive powers, electric motors possess a number of marked advantages. They may be enumerated as follows:

(*a*) The heavy overloads that may be imposed on the electric motor for a short time.
(*b*) The great starting ability due to the economical distribution of weight.
(*c*) The absence of reciprocating parts, giving a uniform torque.
(*d*) The cleanliness and noiselessness of this method of operation.
(*e*) The ease and economy of control of the motors.
(*f*) The high efficiency of the electric motor and distribution systems as applied to traction.

Electric motors of the types used for traction are capable of withstanding heavy overloads. In fact, if properly designed for its continuous capacity, a motor may be loaded until stopped without harm to it, unless the overload be too prolonged. This characteristic is of great value when there is difficulty in starting a train due to any cause.

The weight-distribution of electric motive powers is excellent. In the case of motor cars, all of the train weight may be made available for adhesion, by placing a motor on each axle. This maximum adhesion is seldom demanded; although for a number of reasons single cars are often equipped with four motors. In

steam locomotives, a considerable proportion of the total weight is in the tender with its load of fuel and water. Not only is this feature absent in the electric locomotive, but a larger portion of the weight of the locomotive proper may be placed on the drivers. The effect of this is that the electric engines will be much the lighter for the same hauling power.

In the steam locomotive, the tractive effort in one revolution of the drivers varies over a considerable range, due to the non-uniform effort of the steam during the stroke of the piston. In some cases this will cause slipping of the wheels before the average value of the maximum tractive effort is reached. In the electric locomotive the torque may be applied up to the slipping point of the wheels without difficulty, since, due to the symmetrical design of the motor armature, it gives the same torque in any position; which is also true in those machines where the force is transmitted through cranks and side-rods, if the cranks be "quartered," as is the usual practice.

The cleanliness of electric motors, as compared with steam engines, is unquestioned. In fact, this feature is one of those that have made rapid transit on city streets satisfactory, and is the one thing that has made subway and tunnel operation possible. The absence of smoke, dust and cinders is a great argument, especially since a measurable financial loss is involved in the dirt incident to steam operation. The view has been taken by the courts that persons living along the line of a steam road in a city can recover for damage due to these causes. Noise may be reduced to an almost negligible amount by the use of properly maintained electrical equipment, something impossible with steam; for the sharp blast of the exhaust through the nozzle is necessary to provide sufficient draft in the fire-box.

Electric motors of the various types may be controlled by electrical means to operate at various speeds; and the speed may be reduced to zero for starting or coupling purposes. Although there are some losses incident to greatly reduced speeds which do not appear with steam locomotives, they do not compare unfavorably with losses in the control of other motive powers.

Traction motors are usually designed, not for high efficiency, but for ruggedness and reliability. Commercial machines have very good efficiencies, however. The overall efficiency of the complete electric system will vary from 50 per cent. to 75 per cent. in ordinary cases. Although at first sight these values may

appear low, they are in reality excellent, and better than those of other motive power systems employed in similar service.

The advantages enumerated above are most marked in the first and second classes of roads; but nearly all of them are applicable to the third class also. They are likewise greater in the case of motor car operation than when the power is concentrated in locomotives, though the use of the latter introduces certain compensating advantages which often more than offset the detriments.

In general, the superiority of electric power is great enough to warrant its consideration for any class of railway service; and its use is the more desirable almost in proportion to the density of the traffic, either freight or passenger.

The Railway Problem.—In a broad sense, the railway has much in common with other engineering works. Speaking generally, what is desired is to perform certain functions for the benefit of the public, at the same time making a reasonable profit on the invested capital. In attacking any problem of this character, it is necessary to consider all phases of it in determining whether a project is attractive for the investor. To do this, certain engineering points must be considered in detail, and assumptions made and proved correct. In the following chapters the engineering methods are discussed separately; but the main object, as given in this paragraph, must not be lost sight of.

CHAPTER II

THE MECHANICS OF TRACTION

Fundamental Principles.—The fundamental relations governing the motion of railway trains are derived directly from the laws of motion of any material bodies. For convenience in calculation a number of secondary units have been derived for the solution of railway problems. Since these units are almost universally employed in the literature of the subject, a brief review of their derivation is desirable.

Work and Energy.—When a material body is moved over a given distance, mechanical energy is expended and work is done. By the principle of the conservation of energy, the two must be equal, and the numerical measure of either is the product of the force employed into the distance over which the body has moved, or

$$W = Fs \tag{1}$$

where W is the energy or work, F is the force employed, and s is the distance over which the body is moved.

The above equation expresses the *potential* energy of the body. If we consider a body in motion, especially if the force be a variable one, the equation must be made to express *momentary* changes of distance covered, or

$$dW = Fds \tag{2}$$

From equation (2) may be derived the total energy or work done, by the integration,

$$W = \int_o^s Fds \tag{3}$$

In order to apply equation (3), it is necessary to estimate the change in the distance covered at each portion of the motion. This is most readily done by means of the velocity, which is the rate of change of position with respect to time, or

$$v = \frac{ds}{dt} \tag{4}$$

This may also be written

$$ds = vdt \tag{4a}$$

where v is the velocity, and t the time.

If we use this last value in the above equation for energy, (2), it becomes

$$dW = Fvdt \tag{5}$$

From elementary mechanics we have

$$W = \tfrac{1}{2} Mv^2 \tag{6}$$

where M is the mass of the body in motion.

A differentiation of this last equation, (6), with respect to v, gives

$$dW = Mvdv \tag{7}$$

Acceleration.—We may now equate the two expressions for differential energy, (5) and (7), or

$$Fvdt = Mvdv \tag{8}$$

whence

$$F = M\frac{dv}{dt} \tag{8a}$$

In this equation, $\frac{dv}{dt}$, the rate of change of velocity with respect to time, is better known as the acceleration, a, or

$$F = Ma \tag{9}$$

Equation (9) holds good in any system of notation. In countries where the English system of units is employed, the force F and the mass M are usually measured in pounds, and acceleration a in feet per second per second. Since masses are usually estimated by gravity-measure, it is customary to restate equation (9) as

$$F = \frac{G}{g}a \tag{10}$$

where G is the *weight* of the moving body and g the acceleration due to gravity. In the English system the "gravitation constant" g has a value of approximately 32.2, whence

$$F = \frac{G}{32.2}a \tag{10a}$$

and

$$a = \frac{32.2F}{G} \tag{10b}$$

In equations (10a) and (10b) acceleration a is expressed in feet per second per second, and force, F, and weight, G, in pounds. For use in railway problems these units are inconvenient, the speeds being more readily determined in miles per hour and the accelerations in miles per hour per second; and the weights are of such magnitude that they are better expressed in tons (in the United States the short ton of 2000 lb. is now universally used). Formulæ (10a) and (10b) must therefore be modified for practical use. A mile contains 5280 feet, and an hour $60 \times 60 =$ 3600 seconds; hence a velocity of 1 mile per hr. is equal to $\frac{5280}{3600} =$ 1.467 ft. per sec. If we express accelerations in miles per hour per second by A, then

$$a = 1.467A \tag{11}$$

or

$$A = 0.682a \tag{11a}$$

Employing T to represent weight in short tons, and A to denote accelerations in miles per hr. per sec., as given in equations (11) and (11a), equation (10a) becomes

$$a = 1.467\,A = \frac{32.2F}{2000\,T}$$

whence

$$A = 0.01098\,\frac{F}{T} \tag{12}$$

or, solving for F,

$$F = 91.097\,TA \tag{13}$$

or, in other words, a force of 91.1 lb. applied to a body weighing 1 ton will produce in it an acceleration of 1 mile per hr. per sec. Equations (12) and (13) are the ones usually employed in discussing acceleration of railway trains.

Rotational Acceleration.—Besides the rectilinear acceleration as determined above, it is also necessary to impart to the wheels, axles, gears and motor armatures a motion of rotation. To produce this rotational acceleration an additional amount of force must be employed. This may be determined as follows: Referring to Fig. 2, consider a particle of mass dM, of any of the rotating parts of a car, situated at a distance ρ from the center of rotation. If the angular acceleration of the rotating part be θ, the tangential acceleration of the mass dM at any instant will be

$\rho\theta$, and, from equation (9), the force df_1 to produce that acceleration is $\rho\theta dM$. Since the force df_1 acts at a distance ρ from the center of rotation, its moment is

$$\rho\theta dM \times \rho = \rho^2\theta dM$$

The total moment of the whole rotating mass is

$$\int \rho^2\theta dM = K\theta \tag{14}$$

where K is the moment of inertia of the body about its axis of rotation. It may also be expressed by the relation

$$K = k^2M \tag{15}$$

where k is the radius of gyration and M the total rotating mass. Also

$$r\theta = a \tag{16}$$

or

$$\theta = \frac{a}{r} \tag{16a}$$

where r is the radius of the rotating part considered, and a its tangential acceleration.

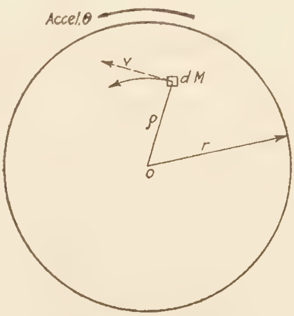


FIG. 2.—Determination of rotational acceleration.

Hence

$$\text{Total moment} = k^2M\frac{a}{r} \tag{17}$$

$$= \frac{k^2}{r} Ma \tag{17a}$$

and

$$f_1 = \frac{\text{Moment}}{r}$$

$$= \left(\frac{k}{r}\right)^2 Ma \tag{18}$$

For a pair of ordinary cast iron car wheels and axle the weight is approximately 1950 lb., and the ratio $\frac{k}{r} = 0.64$. Substituting in equation (18),

$$f_1 = (0.64)^2 \times \frac{1950}{32.2} a = 24.80a$$

This gives the force f_1 lb. to produce a corresponding acceleration in feet per second per second. To transform the equation to our

railway system of units, it is only necessary to multiply by the constant 1.467. Since there are four axles and pairs of wheels on an ordinary car, the value thus found should be multiplied by 4, making the complete expression for the force to produce angular acceleration for a car without electrical equipment

$$f = 24.80 \times 1.467 \times 4A = 145.52A$$

When motor cars are considered, an additional amount of force must be employed besides that for angular acceleration of wheels and axles. It may be determined in the same manner as outlined above.[1] The values will vary with the type and number of motors per car or per locomotive. The following figures are representative of American practice:[2]

PER CENT. OF TOTAL ACCELERATING FORCE REQUIRED FOR ROTATING PARTS

	Per cent.
Steam locomotive and train	2–5
Electric locomotive and heavy freight train	5
Electric locomotive and high-speed passenger train	7
High-speed electric motor cars	7
Low-speed electric motor cars	10

Total Accelerating Force.—The total force required to produce acceleration both of translation and rotation is

$$F = 91.1\,TA + 145.52A$$

or

$$F = A(91.1T + 145.52) \tag{19}$$

for a car without electrical equipment.

In the particular case of a 27.5 ton car equipped with four 38 kw. motors, and geared for a speed of 50 miles per hr., the force required for producing rotational acceleration is 9.55 per cent. of that necessary for rectilinear, making the total force for an acceleration of 1 mile per hr. per sec. equal to 91.1×1.0955, or 99.8 lb. per ton.

In general, a value of 100 lb. per ton may be used with a fair degree of accuracy as the total force required for unit acceleration for electric motor cars, so that equation (19) may be rewritten:

$$F = 100AT \tag{19a}$$

[1] *See also Chapter VII*, "Effect of Rotational Inertia."

[2] *Standard Handbook for Electrical Engineers*, Sec. 13, par. 88, Third Edition.

which is widely used in practice where extreme accuracy is not required. In this book it will be used as a correct approximation.

Train Resistance.—When a train is in motion, a number of forces are always at work tending to reduce its velocity. Some of them are always present; others occur only under certain conditions. It is therefore necessary to state just what is meant by the term "train resistance." As ordinarily defined, it is understood to include those forces which oppose the motion of a train when running on a straight level track at constant speed, and in still air. This portion of the train resistance, which is inherent to operation under the stated conditions, may be divided into the following components:

1. Journal friction.
2. Rolling resistance.
3. Flange friction.
4. Oscillatory resistances.
5. Air resistance.
6. Friction of motor gears and bearings (in motor cars only).

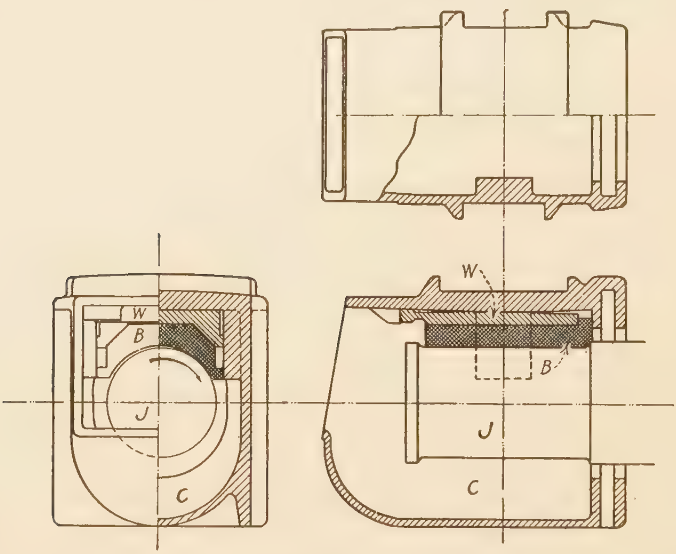
The above resistances are always acting to retard the motion of a train when operating under the conditions stated. In addition to these components, there are others not inherent to the motion of the train itself, but which depend on special conditions of operation. They are:

7. Grade resistance.
8. Curve resistance.
9. Wind resistance.

These additional components may frequently exceed the inherent resistance in amount; and in the operation of freight trains at slow speeds they are usually the more important. They may be grouped under the head "incidental resistances."

Journal Friction.—Friction in the journals of ordinary rolling stock follows the laws of bearing friction in general. A common form of car bearing is shown in Fig. 3, which is a section through the standard 5 × 9 in. journal adopted by the American Electric Railway Engineering Association. The axle is extended to form the journal, *J*, which rotates in the journal bearing or "brass," *B*. Lubrication is provided by placing a quantity of oil-soaked wool waste in the oil cellar, *C*. This packing carries oil from the cellar to the journal by capillary attraction, and so serves to

lubricate the bearing. The principle of lubrication in such a bearing depends on sufficient oil being drawn between the journal and the brass to form a film of lubricant separating the two metal surfaces. When this is done, the friction is that of the molecules of oil against one another, which is comparatively small. If, for any reason, the oil film is broken, the molecular friction of the lubricant is replaced by rubbing friction of metal on metal. The force required is then much increased, and the work done appears in the bearing as heat. If the action is



J, Journal; *B*, bearing brass; *W*, wedge; *C*, oil cellar.

Fig. 3.—Standard A. E. R. E. A. Journal and Bearing.

allowed to continue for any great time, the temperature is raised to a point where any oily waste in the bearing cellar will catch fire, and a "hot-box" results. When a train is standing still, the static pressure of the bearing on the journal will squeeze all the oil out from between the bearing surfaces, so that when the train is started the friction is quite large. As the speed increases, oil is drawn into the bearing, and the friction reduced. The minimum resistance is reached at a speed of about 30 miles per hr. for any given temperature and journal pressure; and beyond this point it becomes greater with increased speed.

Experiments have shown that the friction falls as the pressure per unit area is increased, within the ordinary range of bearing pressures; and it also grows less with rise in temperature up to the point where the viscosity has been reduced so that the oil film cannot be maintained. This is beyond the ordinary range of working temperatures.

If the oil is too fluid, it will not have sufficient viscosity to form a film; and if too thick, not enough will be drawn into the bearing to make the film complete. It is necessary to have oil of the proper viscosity if the lubrication is to be good. Since the viscosity varies with the temperature, a heavier oil is needed in summer than in winter. Variations in the character of the oil used will cause greater differences in the friction than any of the other items considered, and hence it is not possible to give absolute figures for journal friction unless the characteristics of the lubricant used are known.

Flange Friction, Rolling and Oscillatory Resistances.—These resistances are so intermingled that no attempt to separate them has been successful. The causes producing one of them usually gives rise to the others.

Rolling resistance is due to several things. The loaded wheel produces a deflection of the rail, and also compresses it, so that in effect the car is always climbing a small grade. The bending of the rail is augmented by deflections and compression of the ties and the roadbed, and by yielding at the rail joints.

Flange friction is produced by the rubbing of the wheel flanges against the rail heads. This varies with the speed of the train, condition of the trucks, shape of the wheel and the rail and other causes; and also depends to some extent on the track construction and methods of suspension.

Oscillatory resistances are quite indefinite. If the train sways from side to side of the track, it is evident that a certain amount of energy must be absorbed by such motion. They cannot be determined separately, and are usually considered to be those resistances remaining after the other items have been accounted for. They are necessarily closely related to the rolling friction. It is certain that they increase rapidly with the speed, since the force of impact varies as the square of the velocity.

The sum of the flange friction, rolling and oscillatory resistances make up a not inconsiderable portion of the total train resistance. Although the above discussion would indicate that

these items should increase more rapidly than the speed, they are considered by some writers to vary directly with it.

Air Resistance.—In high-speed operation the air resistance is the most important factor of train resistance. This may be divided into three components:

1. Head end resistance.
2. Side friction.
3. Rear suction.

The head end resistance is due to the displacement of the air caused by the passage of the train through it. It is the largest

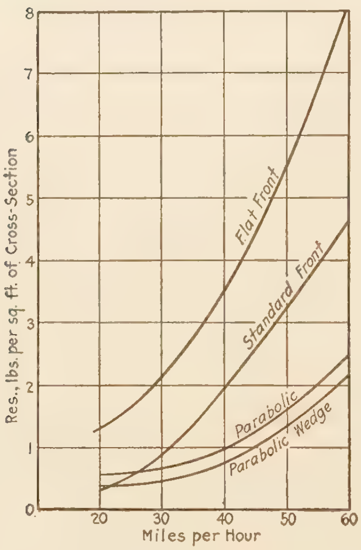


FIG. 4.—Head end air resistance.

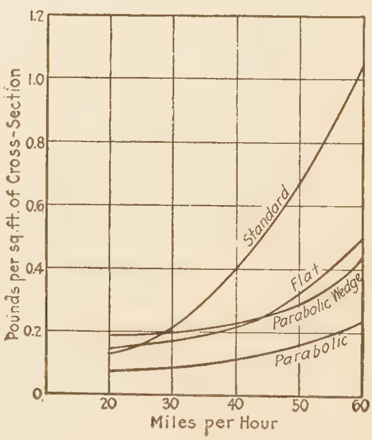


FIG. 5.—Rear end air suction.

part of the air resistance. It depends on the projected area of the front of the train, the shape of the front, and the speed. A number of tests have been made to quantitatively determine its value. Prominent among these are the ones made by the Electric Railway Test Commission, formed by the electric railway interests in connection with the Louisiana Purchase Exposition in 1904,[1] and the so-called "Berlin-Zossen" tests, conducted in

[1] *Report of the Electric Railway Test Commission*, McGraw Publishing Co., 1906.

1901 and 1902–03 by a committee working in conjunction with the German government[1].

The conclusions of both these investigations indicate that the head end air resistance varies as the square of the speed, and has materially different values for various shapes of front end. The results obtained by the Electric Railway Test Commission are summarized in Fig. 4. It appears that a wedge-shaped front offers much less resistance than the ordinary forms used on electric cars.

The rear suction is quite similar to the front end resistance, being due to filling the partial vacuum formed by the passage of a train with air at atmospheric pressure. It follows the same laws, but is less in amount, than the front end resistance. Values of rear suction are shown in Fig. 5. It may be noted that the resistance of the parabolic shaped rear end is less than that of the wedge, which at the front end gives the lowest value.

The side friction is caused by the rubbing of the air against the sides of the car. It also varies approximately as the square of the speed, and for a single car is about one-tenth the sum of the front and rear resistances.

Motor and Gearing Friction.—In the case of electrically driven cars, there is a certain loss due to the friction of the motor armature bearings, the motor axle bearings, and, in the case of geared motors, of the gears. The motor bearing friction is ordinarily included in the losses of the motor, but that of the axle is omitted. It follows the general laws of friction, as in that of the car journals. The gear friction is sometimes included in the motor losses, and in others must be taken with the train resistance. The loss incurred in the transmission of power through a pair of spur gears such as are commonly used in transferring the torque from the armature shaft to the axle, generally runs between 3 per cent. and 9 per cent., depending on the pitch line speed and the condition of the teeth. New gears show a higher loss than those which have worn enough to remove the irregularities due to cutting. The loss again increases considerably after the teeth have become badly worn. For gears in good condition and for moderate pitch line speeds, the loss is about 3½ per cent. of the power transmitted.

[1] *Berlin-Zossen Electric Railway Tests of* 1902–03, McGraw Publishing Co., 1905.

It should be noted that the losses in the gears, and also the mechanical losses in the motors, while supplied electrically when power is being drawn from the electric circuit, must be taken from the momentum of the train when it is coasting. This causes some difference in the values of train resistance in the two cases. The gear loss while the train is coasting is, however, small, since the power transmitted is only sufficient to drive the armature while running light. In case the motors are used for any form of dynamic braking, the loss will of course be larger in proportion to the power drawn from them. The gear losses occur only in cars and locomotives driven by motors acting through gearing, being of course entirely absent in the case of gearless machines.

Determination of Train Resistance.—A number of methods have been employed for the determination of the resistance of cars and trains, the practice depending to some extent on the motive power employed. The resistance of steam trains may be obtained by any one of three methods. The first of these is to place a dynamometer directly behind the tender of the locomotive, and record the drawbar pull. This pull, if obtained with uniform conditions as outlined in the definition at the beginning of the discussion, is a direct measure of the resistance for the speed at which the observation is taken. Results determined in this manner are inaccurate in that the head end resistance is omitted. In the case of long freight trains operating at relatively slow speeds, this is unimportant; but with high-speed passenger trains it may lead to considerable error. In steam locomotive work the inaccuracy is corrected by including the head end resistance in the "machine friction" of the locomotive. If tests made in this way are to be used for determining electric train resistance, care must be taken in interpreting them.

The second method of obtaining the resistance of steam trains consists in taking indicator diagrams at various constant speeds, and from the cylinder performance determining the force supplied to overcome train resistance. This method is liable to all the defects encountered when indicating steam engines under the disadvantages inherent to road tests, and also introduces an error by including the locomotive friction.

The third method consists in allowing a train to coast, and finding the time required to retard from one given speed to

another. This method would appear to be of at least as great accuracy as the last, although it has never met with much favor in the eyes of steam railroad men.

The resistance of electrically equipped trains may be determined readily by operating at constant speed under the proper conditions, and determining the input to the motors. If the efficiency of the motors be determined by a separate test, the corresponding output can be found at once, giving the value of the train resistance directly. This method has met with the greatest favor of late years, and the best and most consistent results have been obtained by its use.

Train Resistance Formulæ.—Ever since the subject of train resistance began to be understood, attempts have been made to render the results of tests universally applicable by presenting them in the form of equations involving the constants of the equipment and the speed. A large number of such formulæ have been published; but their great divergence would indicate either that they are inaccurate or that they are inapplicable over a wide range of conditions of operation. Of these formulæ there are two distinct types: those applying to steam trains, which omit head end resistance, and those applying to electric trains, which include this item. Although the resistance of either kind of train is essentially the same for similar conditions, the above difference will cause considerable variation in the train resistance equation. Unfortunately, investigators do not always specify the class of trains to which their formulæ are applicable.

In obtaining a rational formula for train resistance, it is obvious that several of the components can be grouped together. A portion is sensibly constant at all speeds, a part varies as the speed, and still another as its square. If there are functions of higher powers of the speed, they have not as yet been segregated, and they must be quite unimportant. A rational train resistance formula should then be of the type

$$R = A + BV + CV^2 \qquad (20)$$

where R is the resistance in pounds per ton, V the speed of the train in miles per hour, and A, B and C coefficients determined experimentally.

A formula of the semi-rational type has been developed by Mr. A. H. Armstrong, as follows:

$$R = \frac{50}{\sqrt{T}} + 0.03\ V + \frac{0.002aV^2}{T}\left(1 + \frac{n-1}{10}\right) \qquad (21)$$

in which R is the resistance in lb. per ton,

T is the weight of the *train* in tons,

V is the speed of the train in miles per hr.,

a is the area of cross-section of the train in sq. ft.,

n is the number of cars in the train.

The first term represents largely the bearing friction, the second the rolling resistance, flange friction and a portion of the oscillatory resistance, and the third term the remainder of the oscillatory resistance and the air resistance. The last factor of the third term is to allow for the side air friction if there be more than one car in the train. This formula has given fairly consistent results, and may be safely used in predetermining the train resistance for ordinary American passenger rolling stock.

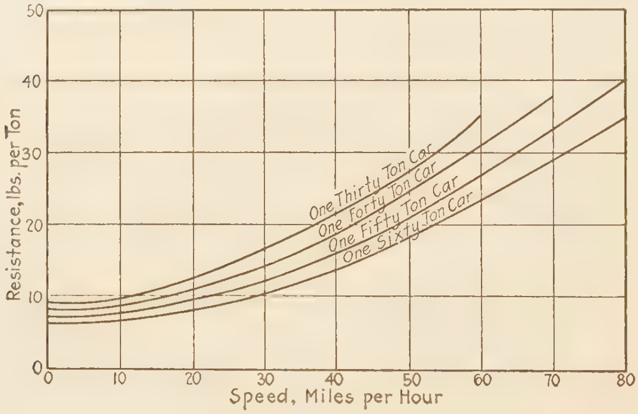


Fig. 6.—Train resistance for cars of different weights.

In Fig. 6 is shown the application of Armstrong's equation for cars of different weights. The curves are of the same general type, and differ only in the first and third terms. In Fig. 7 is shown a series of curves for the resistance of different trains made up of cars of the same weight. The lower resistance per ton as the number of cars in the train is increased is clearly shown.

It should be noted that none of the formulæ for train resistance in the form of equation (20) make allowance for the starting resistance. This will usually be much greater than the resistance after even a very low speed has been attained, on account of the high bearing friction at starting. This has already been referred

to, and accounts for some discrepancies which appear in the application of train resistance equations.

It is more difficult to determine the resistance of freight trains than that of passenger trains, since the former are made up of

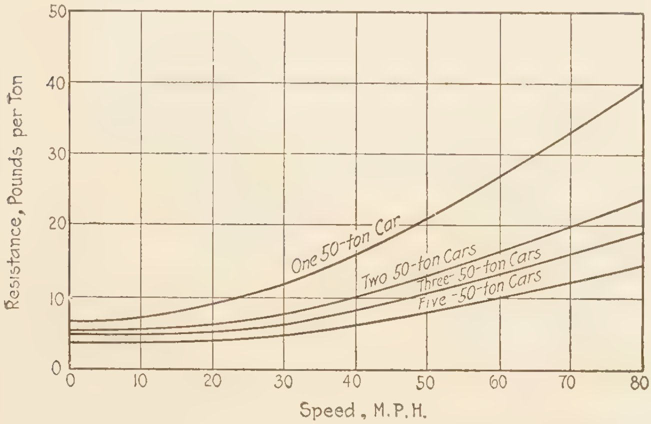


FIG. 7.—Train resistance for different numbers of cars.

cars of widely varying weight and different design. There is moreover a difference in resistance between that found for loaded cars and for empties. The expense of making up complete trains

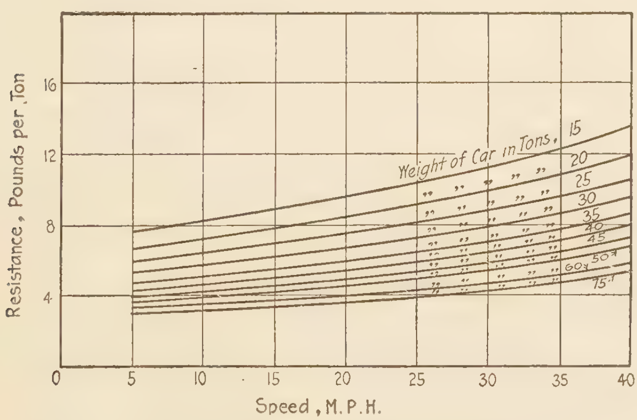


FIG. 8.—Freight train resistance.

of freight cars of one weight and type would be great; and the cost would not be justified, since such trains are not to be found in practice. A better method is to make tests on ordinary trains

of any make-up, and base the resistance on the average car weight. The result of such a series of tests on trains in regular service is shown in Fig. 8, which is from results obtained by Professor Edward C. Schmidt.[1]

These curves were taken with a dynamometer car, and do not include the head end resistance.

Incidental Resistances. Grades.—In surmounting a grade a train has to be lifted through a definite vertical distance. To do this a certain amount of force is required, sufficient to balance the tendency of the train to run down the grade. The measure of this is the value of the gradient, which may be expressed either in

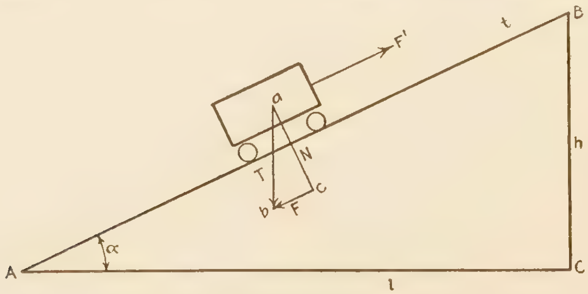


FIG. 9.—Determination of grade resistance.

per cent. rise, or in feet rise per mile. The surveyor, in laying out the track, measures the horizontal distance, l (Fig. 9), and the vertical height h. If a train weighing T tons be on the grade, this weight may be resolved into two components, N normal to the track and F along the track. It is this latter force which must be balanced by the force F' to keep the train in equilibrium. The value of the force F is $T \sin \alpha$. Since N and T are respectively perpendicular to t and l, and angles BCA and bca are right angles, the triangles ABC and abc are similar, and angle BAC = angle bac. Therefore,

$$F' = -F = T \sin \alpha = T\frac{h}{t} \tag{22}$$

It is usually inconvenient to determine $\frac{h}{t}$ directly; but the tangent of the angle α, $\frac{h}{l}$, may be readily found. For ordinary grades the error is negligible in assuming the sine equal to the

[1] EDWARD C. SCHMIDT, "Freight Train Resistance," *Bulletin* 43, Engineering Experiment Station, University of Illinois.

tangent. For example, the error for a 4 per cent. grade, which is about the practical limit, is one-fourth of 1 per cent., and for a 10 per cent. grade, one-half of 1 per cent.

For a rise of 1 ft. per 100, and a train weight of 1 ton,

$$F = 2000 \times \frac{1}{100} = 20 \text{ lb.} \tag{23}$$

For a rise of 1 ft. per mile, and a weight of 1 ton,

$$F = 2000 \times \frac{1}{5280} = 0.3788 \text{ lb.} \tag{24}$$

The force necessary to maintain motion on a grade is therefore 20 lb. per ton for each per cent. of rise, or 0.3788 lb. per ton for each foot per mile. If the train is going down the grade, the force is in the opposite direction, and aids the tractive effort of the motive power.

Virtual Grades.—When the speed of a train is changing, it may be considered that it is virtually on a slope whose resistance is equal to the sum of the resistance of the actual grade and that of one which is equivalent in its effect to the acceleration. A grade of this character is called a "virtual" or "velocity" grade, and the total resistance of a train on it is always equal to that on the actual grade and the resistance corresponding to the force required for acceleration. The virtual grade may be either greater or less than the actual one, depending on whether the train speed is increasing or decreasing; or, in other words, whether the acceleration is positive or negative.

When trains, especially those making infrequent stops, such as heavy freight trains, are operated on roads having a broken profile, it is often possible to approach the up-grades at higher speeds than can be maintained to the summit. The stored kinetic energy will be reduced as the ascent progresses, and be liberated. This energy will aid in lifting the train, thus being converted into potential energy. In effect, the resistance will be less than that due to the actual grade; and, in determining the weight of train that can be hauled by a given locomotive, the virtual grade should preferably be used. It is then important to find the value of the latter, which may readily be done by calculating the liberated kinetic energy due to the difference in speeds between that of approach and at the summit. The length of the grade being known, the average velocity dur-

ing ascent can be found, and the force equivalent to the converted energy determined. This force, subtracted from the resistance of the actual grade, gives that corresponding to the virtual grade. From this the resistance in pounds per ton, and the equivalent rise in feet per mile or in per cent. may be found directly by equations (23) or (24). It is evident that virtual grades are always limited in length.

The Ruling Grade.—In any given section of track, the maximum gradient encountered is known as the "ruling grade," whether it be an actual or a virtual one. The maximum load which a given motive power can haul on a certain division of a road is determined by the greatest tractive effort it can exert on the ruling grade. In general, ruling grades are not of such great importance in the case of electric roads as in steam roads, since the electric motors can usually be forced beyond their normal rating for a short time, as in climbing the ruling grade; whereas the maximum output of the steam locomotive is practically a fixed quantity, which cannot be exceeded for even a short period.

Curves.—In American railway practice it is customary to rate curves in degrees of central angle subtended by a chord of 100 ft. This method follows from the ordinary procedure in laying out curves with a transit. At the point of curvature, A, Fig. 10, the instrument is set up, and angles DAB, FAC, etc., laid off, each equal to one-half the "degree" of the curve. In the case of a 1° curve, the angle AOB is 1° and DAB is 0° 30′. Referring to Fig. 10, if AB = 100 ft., then

$$\frac{AK}{AO} = \sin \frac{\alpha}{2} \tag{25}$$

$$\frac{50}{AO} = \sin 0° \, 30' = 0.00873,$$

from which AO = 5730 ft. In general, if D is the degree of the curve, and r its radius,

$$\sin \tfrac{1}{2} D = \frac{50}{r} \tag{26}$$

and

$$r = 50 \csc \tfrac{1}{2} D \tag{26a}$$

Approximately, the radius for ordinary curves may be taken as $\frac{5730}{D}$ ft. In curves of large degree and correspondingly small

radius this assumption leads to considerable error; and when laying them out chords of 50 ft. or less are used in place of the 100 ft. which is employed for those of longer radius. In street railway work, where the radii are extremely short, being from 35 ft. to 100 ft., the curves are ordinarily designated by the radius in feet. In such cases they are not usually laid out with instruments; but the rails are shaped and assembled by the manufacturer before shipment and are installed as a complete unit. Such track is referred to under the general term "special work."

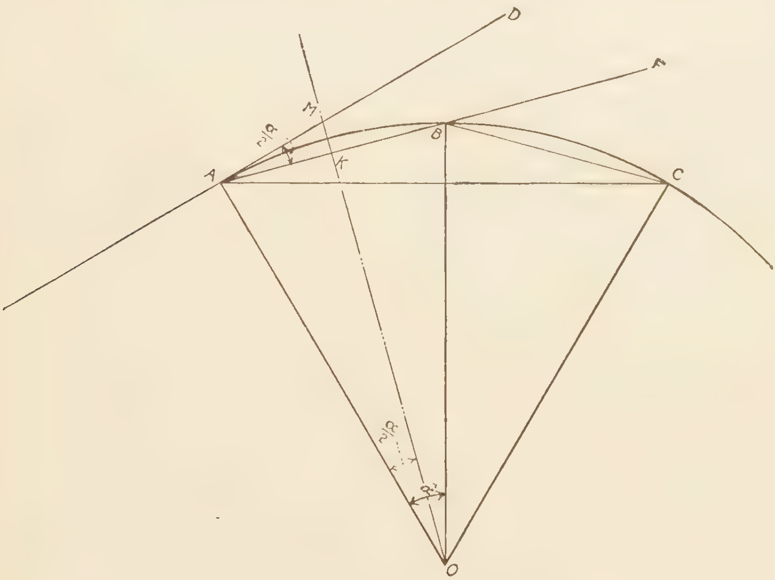


Fig. 10.—Method of laying out curves.

In high-speed railway work an abrupt change of direction from a tangent to a circular curve would cause difficulty in operation, and might even make a train leave the track. To obviate this difficulty the first portion of a curve is some form of spiral which makes an easy transition from the tangent to the circular arc. A number of such curves are in use and methods of construction may be found in any good handbook on railway location.

Since a body in motion tends to travel in a straight line, a force must be introduced in order to cause it to change its direction. The value of this force depends on the speed and weight of the train and the amount of curvature; it may be supplied by pres-

sure of the wheel flanges against the outer rail of the track or by gravity. In the latter case the force is obtained by locating the outer rail of the track at a higher level than the inner. This is known as the *superelevation of the outer rail.*

In Fig. 11 consider a car of weight $G = Mg$ on a curve of radius r, the superelevation of the outer rail being such that the track makes an angle ϕ with the horizontal. The force G due to the weight of the car will have a tendency to pull the train toward the center of the curve. The centrifugal force has a value of $\frac{Mv^2}{r}$

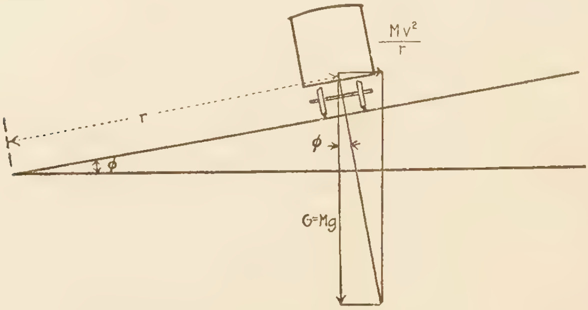


FIG. 11.—Centrifugal effect of curves.

exerted in a horizontal direction. From the figure it may be seen that the resultant of these forces will be normal to the track when

$$\tan \phi = \frac{v^2}{rg} \tag{27}$$

It is evident from the above discussion that the superelevation of a curve is correct for one speed, and for that speed only. If the velocity be greater than this value, the reaction from the track will not supply all of the directive force required; the remainder must be furnished by pressure of the flanges against the outer rail; if less than the balancing speed, the force supplied by the track reaction will be greater than necessary, and the train will fall toward the inner rail, the pressure being taken by the flanges of the inner wheels. In either of these cases there will be an amount of flange friction additional to that occurring on straight track.

Since the tracks of ordinary railroads must be used in common by fast and by slow trains, it is not possible to compensate the curves for all of them. A compromise is usually effected so that

the superelevation is too great for the freight trains and too small for the passenger trains. The general result will be to reduce the resistance on curves for all of them, and to make operation safe at speeds up to the maximum used. The proper choice of a mean velocity for which the compensation should be calculated depends on the relation between the speeds of different classes of trains and the relative numbers operated.

A certain amount of friction is also present due to swinging the trucks from their normal position under the cars. The total effect is to increase the train resistance. Experiments indicate that this increase in train resistance averages from 0.5 lb. to 1.5 lb. per ton per degree of curvature.

Wind Resistance.—Natural winds affect the operation of trains by changing the relative velocity of the train with respect to the air, and hence vary the air resistance. For example, a train operating at 40 miles per hr. against a head wind blowing at the rate of 20 miles per hr. will have the same wind resistance as though it were moving through still air at 60 miles per hr. If operating in the opposite direction (*i.e.*, with the wind) the effect will be the same as the air resistance met by moving through still air at 20 miles per hr. Quartering and side winds also affect train resistance by introducing additional flange friction, the wheels being crowded against the rails on the "leeward" side. In general these results are indeterminate in amount.

The Speed–Time Curve.—In order to make a rational comparison of train performance under varying conditions of operation it is necessary to adopt some standard method of reporting results. This need has led to the use of a series of curves, all plotted with time as their abscissæ. The ordinates of this group of curves may be any of the factors which vary with the time, and include the distance covered, the speed, the acceleration, the tractive effort, and the electrical quantities current, e.m.f. and power. Of the mechanical values, distance is the fundamental one; in the equations at the beginning of this chapter some of those which depend on the distance are derived. It is seen that velocity is the rate of change of distance with respect to time, or

$$v = \frac{ds}{dt} \tag{4}$$

Acceleration is the rate of change of velocity with respect to time, or

$$a = \frac{dv}{dt} \tag{28}$$

From the relations of these two equations it may be seen that acceleration is the second derivative of the distance with respect to time, or

$$a = \frac{d^2s}{dt^2} \tag{29}$$

In certain problems involving excessive acceleration and retardation, it has been found that a high rate of change of velocity can be maintained without discomfort if it is reached gradually. This brings into use the rate of change of the acceleration, giving the relation

$$\frac{da}{dt} = \frac{d^2v}{dt^2} = \frac{d^3s}{dt^3} \tag{30}$$

In a similar manner, the velocity is the first integral of the acceleration, as

$$v = \int a dt \tag{31}$$

The distance is the first integral of the velocity, and the second integral of the acceleration.

$$s = \int v dt = \int \int a dt \tag{32}$$

The use of graphical methods for the representation of train motion brings in these relations, and the performance may be shown by means of the distance–time, speed–time, or acceleration–time curves, as desired. If a distance–time curve be differentiated with respect to time, the first differential curve will be that between speed and time, and the second differential curve that between acceleration and time. Similarly, the first integral curve of the acceleration–time curve is the speed–time curve, and the second integral curve the distance–time curve. If any one of the three curves be plotted, it is a simple matter to derive the other two. Since the area enclosed between a curve and its axis of abscissæ is a measure of the integral, a fairly definite idea of that value may be found by inspection. In like manner, the slope of a curve is a measure of its derivative, and the general form of the differential curve may be approximated. For this reason, more information can be obtained by the use of the speed–time curve than by employing either the distance–time curve or the acceleration–time curve for depicting the motion of a train.

Components of the Speed–Time Curve.—In ordinary railway operation, a train starts from rest, and its speed is increased with a rapid acceleration, which will usually fall off as the speed is increased, until the train operates at constant speed. The train may then be allowed to coast without the use of power, after which it is stopped rapidly by application of the brakes.

Acceleration Curve.—In order to produce motion, a certain force must be used, which can be calculated quantitatively if the weight of the train and the required acceleration are known; or the acceleration can be determined if the force and the train weight are given. The method of calculation is that indicated by equations (12) and (19). If the force remains constant, the train will be accelerated at a uniform rate; but if the force is variable, the acceleration will fluctuate correspondingly. If the law of variation of the accelerating force (tractive effort) can be stated in the form of an equation, then the resulting acceleration and the speed at any instant can be determined analytically. Ordinarily, the relation between tractive effort and time is so intricate that no exact expression for it can be found. In any case it is too complex for easy mathematical analysis. Recourse is usually had to a graphical method of treatment, which facilitates the calculation materially.

As the speed of the train increases, the train resistance becomes greater, while at the same time the tractive effort, as supplied by nearly all motive powers, diminishes. A speed will be reached where the train resistance will have increased to a point where it just equals the tractive effort. It is evident that there can then be no further acceleration, and that the speed must become constant at this limiting value. This is often referred to as the "balancing speed." It is always the same for constant conditions, but varies with the grade and the other incidental resistances which may occur. The train will continue to run at this speed until the conditions change, or until power is cut off.

Coasting Curve.—When no power is supplied to the moving train, it will continue in motion, but will be retarded at a rate which depends on the value of the train resistance. This retardation becomes less as the speed decreases, since the train resistance diminishes with reduction in speed. In case the train is on a down grade which gives a force great enough to equal or

exceed the train resistance, the train will coast at constant or even increasing speed.

Braking Curve.—To stop a train by allowing it to coast to a standstill would be impractical, and in some cases impossible; hence a retarding force additional to the train resistance must be introduced to cause more rapid stopping. This force is ordinarily supplied by some form of brake. In ordinary railway practice the force supplied is due to the friction of metallic shoes pressing against the treads of the wheels, although other methods are sometimes employed. A discussion of this topic is given in Chapter VII.

The dynamic relations while braking are precisely the same as those existing during acceleration, except that the main force is reversed in direction. The acceleration is therefore negative. Its value may be determined quantitatively by the application of the same equations as used for a consideration of acceleration, care being taken that the algebraic signs are correctly interpreted.

Calculation of Speed–Time Curves.—The problem of plotting the speed–time curve from given data is one which is constantly recurring in railway work; and it is desirable to have at hand a simple and accurate means of making the determination. An inspection of equations (28) to (32) gives the basis of the method available for making the calculation.

The most convenient way of determining the graphical representation of the speed–time relation is to locate points on a sheet of coördinate paper for a number of values lying along the curve, these points being taken sufficiently close together to give the required accuracy, and the curve plotted through them. The closer they are taken together, the more accurate is the curve. The data given in the statement of the problem usually are the tractive effort and the speed to which it corresponds. In other words, the information is that derived from the characteristic curve of the motive power, such as the curve of the series railway motor, Fig. 19. From equations (13), (19) or (19a) the acceleration produced by the motor tractive effort may be found at once. This gives us the speed and the corresponding value of acceleration, from which the time must be calculated. The means of doing this is to use the relation

$$a = \frac{dv}{dt} \tag{28}$$

which may be rewritten

$$dt = \frac{dv}{a} \tag{28a}$$

This shows at once that there is no easy way of getting the summation of the time increments for a given run, since it is not possible to have a simple equation expressing the relation between speed and tractive effort of the motive power. The total elapsed time from any reference point must be the summation of a large number of increments; and the result obtained depends to a large extent on the accuracy of the method employed for determining the successive time increments. Any graphical method for plotting speed–time curves thus consists of approximating the value of time corresponding to a definite acceleration.

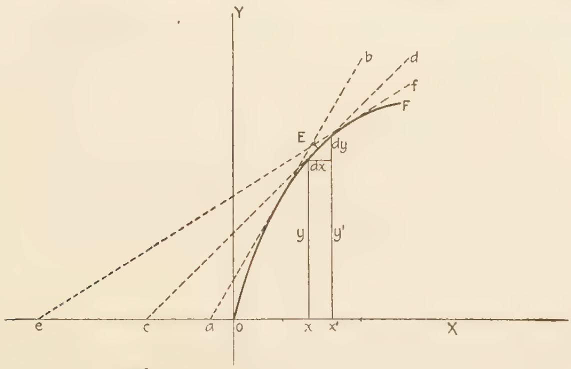


FIG. 12.—Determination of time increments.
In this figure the increments dy and dx are assumed to be infinitesimal.

Mr. C. O. Mailloux[1] has resolved the problem into the following form: "Given the ordinate, y, and the slope of the curve, $\frac{dy}{dx}$, at any point of a curve, to find the abscissa, x, corresponding to the ordinate, or the distance of the ordinate from the Y-axis." Two cases exist—the first where the slope is positive, comprising all acceleration curves; and the second where the slope is negative, which includes all retardation curves. In the former case the curves are usually concave to the X-axis, and in the latter may be either concave or convex to it.

In Fig. 12 the curve OEF represents any portion of a speed-time

[1] C. O. MAILLOUX, "Notes on the Plotting of Speed–Time Curves," *Transactions* A. I. E. E., Vol. XIX, p. 984 (1902). The following discussion is based on this paper.

curve with a positive slope (*i.e.*, an acceleration curve). Consider lines drawn tangent to the curve at various points, as ab, cd, ef. Also take two ordinates y and y', which are very close together, and which may be assumed to include the portion of the speed-time curve at the point of tangency, E, of the line cd. The difference between these is dy, and we may write

$$dy = y' - y \tag{33}$$

The corresponding difference between the abscissæ, dx, is

$$dx = x' - x \tag{34}$$

In order that the two ordinates may be considered to be at the same point of tangency, E, the distance between them must be infinitely small.

The application of similar triangles to Fig. 12 gives the relation

$$\frac{y'}{cx'} = \frac{y}{cx} = \frac{dy}{dx} \tag{35}$$

which expresses the well-known fact that the ordinate y at the point of tangency, divided by the sub-tangent cx, is a measure of the differential at that point. From this relation the value of $\frac{dy}{dx}$ can be determined.

The assumption that has been made, that the increment of ordinate, dy, is infinitesimal, makes it of no value in the plotting of curves. For ordinary purposes it must be increased to some finite value. This makes necessary a re-statement of equations (33) and (34) as follows (see Fig. 13):

$$x' - x = \Delta x \tag{36}$$

$$y' - y = \Delta y \tag{37}$$

in which Δy is the increment of ordinate which corresponds to the increment of abscissa Δx.

The essential difference between the infinitesimal and the finite statements, as given in equations (33) and (34), and (36) and (37), is that while in the former case the ordinates are taken so close together that there is no appreciable difference in the values of $\frac{dy}{dx}$ whether measured by the tangent at the point of the curve having the ordinate y, or that with the ordinate y', it may not hold true in the latter. This is shown in Fig. 13,

which is purposely exaggerated. At the point E, the differential is

$$\frac{dy}{dx} = \frac{y}{cx} \tag{38}$$

while at the point F it is

$$\frac{dy'}{dx'} = \frac{y'}{ex'} \tag{39}$$

It may thus be seen that the differential coefficient cannot be represented by any single value when the increment of ordinate is large enough that a material change in the slope of the curve is included.

The correct value of the differential coefficient will, in general, correspond to some intermediate point, such as D. Drawing

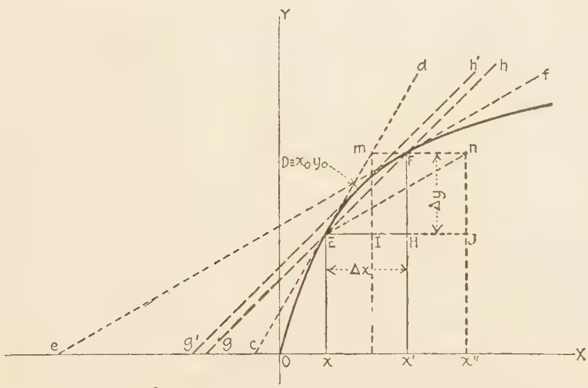


FIG. 13.—Practical method for estimating acceleration.

In this figure the speed increment, Δy, and the corresponding time increment, Δx, are taken as finite values. Compare with Fig. 12.

the line gh parallel to the tangent $g'h'$ through this point, the differential triangle EFH is produced, which is similar to the differential triangle corresponding to the point D. We can therefore write

$$\frac{dy_0}{dx_0} = \frac{\Delta y}{\Delta x} \tag{40}$$

where x_0, y_0, are the coördinates of the point D.

An inspection of the triangles EmI, EFH and EnJ shows the difference in the magnitude of Δx as obtained when using the values of differential corresponding to x, x_0 and x', respectively. In a majority of curves, the point D is approximately midway between E and F. When y and y' are taken sufficiently close

together, the error made by assuming this condition to be true becomes negligible. The value of the differential may then be taken as that corresponding to the average point between those of y and y', so that

$$y'' = \frac{y + y'}{2} \tag{41}$$

The closer the values of y and y' are taken together, the smaller will be the error introduced by making this approximation.

Total Force for Train Operation.—A study of the foregoing paragraphs indicates that a number of forces are always present, which govern the total amount of power which must be supplied to the moving train. If a train is moving at constant speed through still air on a straight level track, the only force required is that to overcome the normal train resistance; but if it is on a grade, or on a curve, or in the presence of a natural wind, a variation in the force becomes necessary if the train is to maintain its speed. If the speed of the train is changing, still other forces act.

The laws of motion show that the resultant of all forces acting on a body is their algebraic or vector sum. Since all the forces which concern the movement of trains act parallel to the track, the algebraic sum gives a correct representation of the total. Using the following notation:

R = force for overcoming train resistance,
G = force for overcoming (up) grades,
C = force for overcoming curves,
P = force for producing (positive) acceleration,
F = total force to be supplied by the motive power,

we may then state as an equation the value of total force

$$F = R \pm G + C \pm P \tag{42}$$

In this statement the value of P must be taken to include both force for linear and for rotational acceleration. The value of G is positive on up grades, since it acts as a resistance, or opposes the force F; on down grades it is negative. The value of P is positive when the speed is increasing (*i.e.*, when the acceleration is positive), and becomes negative when the speed is decreasing from any cause. In other words, the kinetic energy increases directly with the (square of) speed.

At the end of every practical run, it is necessary to bring the train to rest by the application of an external retarding force.

This phenomenon is known as braking, and will be taken up in detail in a later chapter. The necessary value of braking force may, however, be determined by an equation similar to the one above. Using the same notation, and calling the external braking force B, we have,

$$B = -R \mp G - C + P \tag{43}$$

It is to be noted that the signs of R, G and C are reversed; during retardation these resistances hasten the change of velocity. P is always positive, *i.e.*, the change in motion is always in the same direction as the retarding force, in normal braking.

Plotting Speed–Time Curves.—The relations outlined above give a practical method of plotting speed–time curves. The arrangement involving the least complication is to make an analytical calculation of the time increments (Δx), assuming speed increments (Δy) sufficiently close together to keep the error within the required limits. The accuracy will depend on the conditions of the individual problem, so that no definite limits for the speed increments can be stated. It must be remembered that the calculations are somewhat tedious, and need considerable care, to prevent inaccuracy. Since the time increments must be added together to give the total time, the errors are likely to be cumulative, and cannot be expected to annul one another.

In the practical calculation, the tractive effort curve of the motor is used to get the values of acceleration corresponding to various speeds. From this the average acceleration during the increment is found, and from it the time increment. The total elapsed time is obtained by adding together these latter.

To reduce the labor incident to a large number of such calculations, several methods have been advanced to determine the speed–time curve graphically. Of these, the one most used is that proposed by Mailloux.[1] In his method the tractive effort of the motor is replaced by the acceleration which it will produce on the given equipment, and is plotted against speed, as shown in Fig. 14. This is termed the "gross acceleration." The "net acceleration," which is the one actually produced on the train, is determined by subtracting the equivalent negative acceleration due to the train resistance. This is the result on straight level track. When

[1] C. O. Mailloux, "Notes on the Plotting of Speed–Time Curves," *Transactions* A. I. E. E., Vol. XIX, p. 984 (1902).

grades are encountered, a constant force is introduced, amounting to 20 lb. per ton for each per cent. of grade. It is evident that the ordinate of the net acceleration curve will be increased or diminished by the corresponding amount, as shown by the figures at the right of the chart. This has the effect of raising or lowering the base line to the place indicated by the value of grade. Curves may be similarly treated, except that their effect is always opposed to the direction of motion.

Having determined the acceleration at any particular speed from a chart similar to Fig. 14, the corresponding time increment may be found from equation (28a), which may be re-stated

$$\Delta t = \Delta v \frac{1}{a} \tag{28b}$$

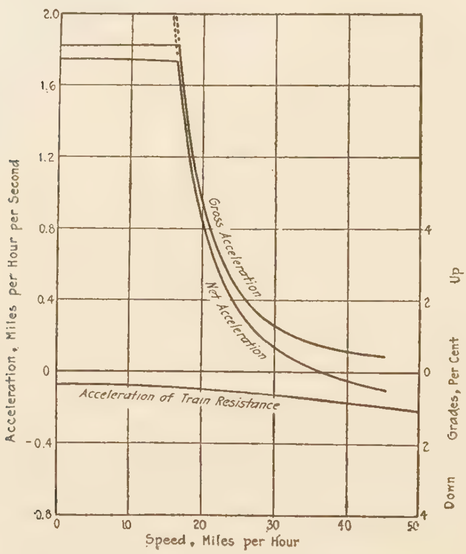


FIG. 14.—Chart of accelerations.

This normally involves the calculation of $\frac{1}{a}$; but if a curve is plotted between natural numbers and their reciprocals, the values of a may be taken from the chart of accelerations with dividers, or by other convenient methods, and the corresponding result for $\frac{1}{a}$ read from the reciprocal chart. If the speed increment is unity, it is evident that the time will be given directly

by this method. If it is desired to use other speed increments, a series of curves may be drawn between natural numbers and one-half, one-tenth, twice, ten times, etc., the actual values of reciprocals. With such a chart the determination of the speed–time curve is relatively quite simple, and the detailed calculations are all dispensed with. It is evident that a new curve of accelerations must be made for each different motor, or for the same motor with different equipments; while the chart of reciprocals is equally good for all cases.[1]

Power for Train Movement.—Having determined the force necessary for train propulsion, as in equation (42), it is easy to calculate the power required at any instant if the speed be known. This is, in horsepower,

$$HP = \frac{Fv}{550} \tag{44}$$

where F is the total tractive effort in pounds, and v the speed in feet per second. If the speed is stated in miles per hour, V, the equation becomes

$$HP = \frac{5280FV}{60 \times 33{,}000} \tag{44a}$$

To express the power in kilowatts, we have

$$KW = \frac{Fv}{737.6} \tag{45}$$

where F is in pounds and v in feet per second. Using speed in miles per hour, this reduces to

$$KW = \frac{5280FV}{60 \times 44{,}256.7} = \frac{FV}{503} \tag{45a}$$

[1] A more complete and simpler method for plotting the speed-time curve is contained in Chapters VIII–IX of Bulletin 90 of the Engineering Experiment Station, University of Illinois, "Some Graphical Solutions of Electric Railway Problems," by A. M. Buck.

CHAPTER III

MOTORS FOR TRACTION

Functions of Motive Powers.—Any motive power for railway service has two definite functions:

1. To accelerate a train from rest.
2. To maintain it in motion at a predetermined speed.

These functions may be performed by almost any form of electric motor now known; but a few types possess inherent characteristics so much better suited to the purpose than the others that they are used almost exclusively.

Electric Distribution Systems.—Electrical apparatus is usually operated on one of two well-defined systems: the constant-current or the constant-potential. Although it is not impossible to operate motors on a moving vehicle from a constant-current supply, the difficulties are so great that after a few trials it has been entirely abandoned for this service. The constant-potential system, on the other hand, readily lends itself to the purpose of distributing energy in large or small amounts, and is especially adapted for serving moving cars or locomotives. Its use has been so very successful that at the present time it is the only system of distribution employed on electric railways. The entire discussion of electrical equipment in this book will be confined to a consideration of constant-potential systems.

The systems for supply of electrical energy may be further classified according to the kind of current: alternating or direct. With the latter there can be but one variation in the conditions of the supply—the line pressure. The former may be of any commercial potential, frequency or phase; for railway service a comparatively limited number of potentials and frequencies have been standardized, and the three-phase and single-phase systems are used exclusively when alternating current is employed.

Classification of Electric Motors.—Electric motors of all

types may be classified either according to the kind of circuit on which they may be operated, or to their inherent characteristics. In the former classification, the natural divisions are alternating current and direct current. The most important types of motors are listed below.

I. Motors for Operation on Alternating-current Circuits:

- Single-phase
  - Synchronous
  - Asynchronous
    - Induction
      - Squirrel-cage
      - Wound secondary
    - Commutator
      - Series
        - Plain
        - Compensated
          - Conductive
          - Inductive
      - Repulsion
- Polyphase (three-phase)
  - Synchronous
  - Asynchronous
    - Induction
      - Squirrel-cage
      - Wound secondary
    - Commutator
      - Various types

II. Motors for Operation on Direct-current Circuits:

- Series
- Shunt
- Compound
  - Cumulative winding
  - Differential winding.

The principal characteristics of the various types of motors are those of torque and speed. Of the two, it is much more useful to classify them as regards the latter. In this table only two speed classifications are given: constant and variable. Several of the motors may have performance which is intermediate between true constant speed and what is known as "variable speed." Such types have either been omitted or included with one or the other class.

III. Classification as Regards Speed Characteristics:

- Constant speed
  - Shunt direct current
  - Synchronous
  - Induction
  - Differential
- Variable speed
  - Series direct current
  - Series alternating current
  - Repulsion
  - Cumulative compound

Consider first the two principal types of direct-current motors, the shunt-wound and the series-wound machines. The entire difference between them lies in the connections of the field windings, in the former the field being connected in series with the armature, and in parallel with it in the latter type. The shunt motor, having its field excited by a winding connected to the supply circuit independent of the armature, has a field of sensibly constant magnetic strength; while in the series machine the field strength is directly dependent on the current drawn through the armature.

Torque Characteristics.—In any electric motor, the torque developed by the armature is proportional to the product of the

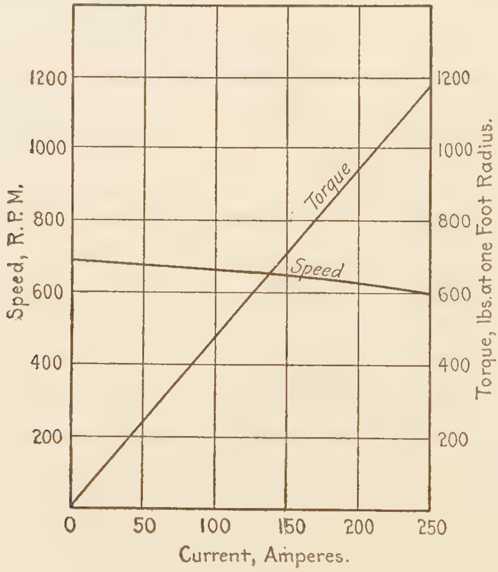


FIG. 15.—Characteristic curves of shunt motor.

field flux, the number and arrangement of conductors on the armature, and the current through them. In the case of a motor having a constant field strength, the torque is directly proportional to the armature current, since for any particular design the number of armature conductors is fixed. This is substantially the condition which exists in the shunt motor. Although there is a small reduction of field flux with increase of armature current, the field strength may be considered sensibly constant, hence a curve drawn between armature current and torque will be practically a straight line, as shown in Fig. 15.

Consider a motor whose field current is proportional to its armature current, the permeability of the magnetic circuit remaining constant. The field flux is then directly proportional to the armature current; and the torque, depending as it does on the product of the field flux and the armature current, varies as the square of the latter (see curve *A*, Fig. 16). Such a relation would exist in the case of a series motor with an unsaturated magnetic circuit. Practically, it is not attainable, due to variations in the permeability of magnetic materials with changes in magnetizing force.

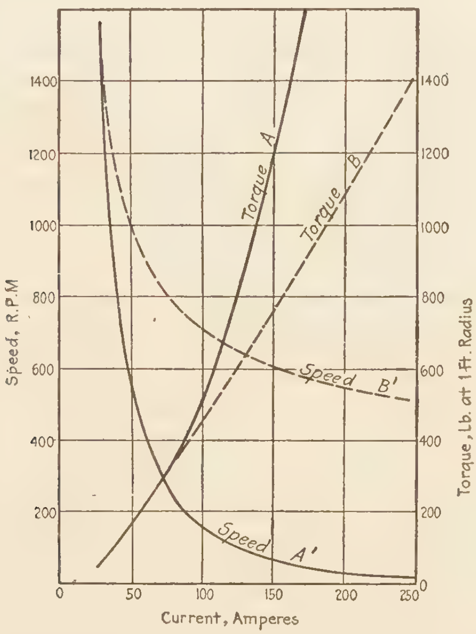


Fig. 16.—Characteristic curves of series motor.

In the last example, if the area of the magnetic circuit be restricted, the field will become "saturated" with large values of current. As ordinarily used, the term "saturation" does not imply that there is no gain in flux with increase of magnetizing current. Even though the magnetic material were incapable of carrying any further induction than a certain maximum value, the flux would vary with the magnetizing current at the same rate as it would with a magnetic circuit composed wholly of air. This condition is far beyond any magnetic densities used in

practice. Since, however, the change in flux is not proportional to the variation of field current, the torque will be less than in the case of the unsaturated motor. The torque–current curve will thus lie between those for the shunt motor and the unsaturated series motor (curve *B*, Fig. 16).

Speed Characteristics.—The counter e.m.f. of a direct-current motor is proportional to the product of field flux, the number and arrangement of conductors on the armature, and its speed; hence

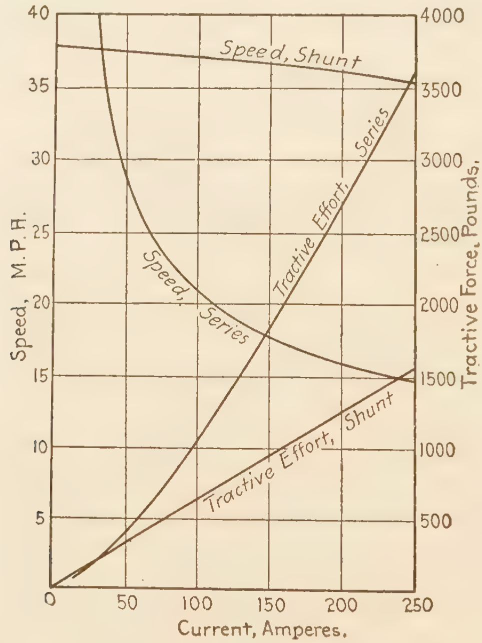


FIG. 17.—Comparison of series and shunt motors.

the latter varies directly with the counter e.m.f. and inversely with the field flux. Since the fall of potential due to resistance of the motor windings is a comparatively small amount, the counter e.m.f. to be developed is nearly constant, and it follows that the speed of a motor with a constant field strength varies but little with the armature current. This is practically the case of the shunt motor, the drop in speed from no load to full load being quite small in a well-designed machine (Fig. 15).

In a motor whose field strength is proportional to the armature current, such as the hypothetical "unsaturated" series motor, the

speed must fall in inverse proportion to the armature current, for it varies inversely with the field flux. The speed curve of such a machine is an equilateral hyperbola, as shown at A', Fig. 16. For the practical series motor, with saturated field, the decrease of speed with load is less rapid (B', Fig. 16). It will, however, fall much more than is the case with the shunt motor of equal rating.

From the preceding discussion it may be noted that for values of current below full load the shunt motor gives more torque per ampere than the series motor, while above this point the conditions are reversed. Where a large amount of torque is needed at reduced speeds, as in the case of starting a train, the series motor gives a certain tractive effort with less load on the line than the shunt motor. If the shunt motor and the series motor are of equal capacity, the former will be able to accelerate the train at the maximum rate practically up to its full speed; but this is considerably lower than the maximum speed of the corresponding series machine. In case a comparison is desired on the basis of motors having the same "balancing" or free-running speed, they will be as shown in Fig. 17. Here the series motor is the same as in the preceding comparison, but the characteristics of the shunt motor are changed, by gearing or otherwise, to increase the speed without changing the horsepower output. The torque is correspondingly lowered. It will be seen at once that this shunt motor cannot possibly give the same accelerating torque as the series motor without imposing an excessive overload on the former; and the torque corresponding to a given value of current is much less than for the series motor. The shunt motor has one advantage, in that it can accelerate the train at the maximum rate up to practically full speed. This partially, but not wholly, compensates for the lower acceleration, since the series motor can only produce its maximum torque up to about half speed. This advantage is slight, as may be seen from Fig. 18, which shows speed–time curves produced by the application to the starting of a particular train of each of the three motors considered. The speed–time curves are based on the application of a maximum value of one and one-half times full-load current during the acceleration period. The series motor gives the highest acceleration, but this falls off from about half speed up to full speed, which is reached only after a long time. The shunt motors, on the other hand, give maximum accelera-

tion until the full running speed is reached, after which the speed is constant.

The advantage of the series motor is greatest where the run is relatively short. In many railways, especially those of the first and second classes mentioned in Chapter I, the motors are not allowed to accelerate up to the point where full speed is attained, but the car is stopped after a relatively short period of operation. With long runs, the time spent in acceleration is comparatively unimportant, and a lower rate is permissible. For this latter service the shunt motor would have the advantage of operating at practically constant speed under all conditions of track. The

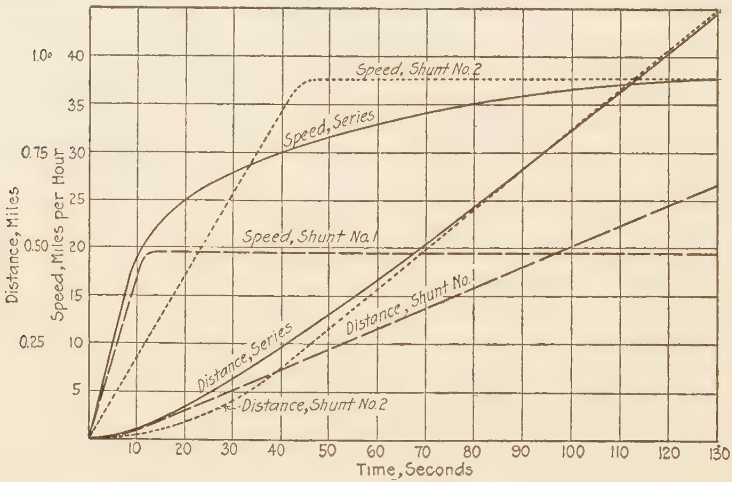


Fig. 18.—Comparative speed-time curves with series and shunt motors.

advantages of the series type of motor so far outweigh those of the shunt, that up to the present time the latter has not been seriously considered for traction. Its counterpart for alternating-current operation, the polyphase induction motor, has not only received favorable attention, but is actually used in a large number of equipments operating in Europe. This success is partly due to the fact that it is the most rugged and efficient type of alternating-current motor yet designed.

The Direct-Current Series Motor.—The direct-current series motor has been used for traction ever since the first practical electric roads were built. Other types of motor have been used from time to time, but none has the excellent operating characteristics of the series machine. Since about 97 per cent. of all the

electric railway mileage in the United States is operated with direct-current series motors, a careful study of their characteristics is necessary.

The general performance of this type of motor has already been discussed briefly. The salient characteristics are a torque which increases with the load at a rate greater than the first power of the current, and a speed which falls off rapidly with it, especially at the smaller loads. These curves may be seen in Fig. 19, which gives the performance of a 56 kw. (1 hr. rating) railway motor.

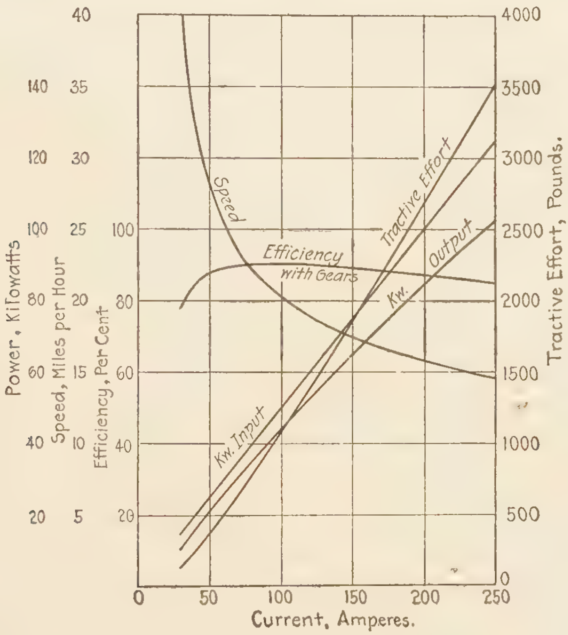


FIG. 19.—Curves for typical series railway motor.

Variation of Speed Characteristic.—It must be noted that although the series motor is usually referred to as a "variable speed" machine, there is for any given value of torque a corresponding definite speed at which the motor will operate; so that, if the tractive effort is constant, the motor will run at one fixed speed. If it is necessary that a train be propelled at varying speeds when the track alignment is uniform, some means must be introduced into the equipment by which the motor speed will be altered to suit the conditions. One possible method of doing this

is by changing the gear ratio. This means is actually employed in the gasoline automobile. It is not, however, necessary to use such a method with the series motor, since a variation in the e.m.f. supplied the motor will cause a change in the speed for a given tractive effort.

The speed characteristic may be readily altered by varying the potential at the motor terminals; this may be accomplished directly by changing the e.m.f. supplied the motor, or by placing resistance in series with it. Details of methods for securing these results will be taken up in Chapter V.

The counter e.m.f. developed by a direct-current motor operating on a constant-potential circuit must be equal to the impressed e.m.f. less the IR drop in the windings. Since the resistance of a well-designed motor is quite low, the IR drop will be but a small portion of the impressed potential; it is rarely more than one-tenth of this value even at heavy loads. The counter e.m.f. must therefore be nearly constant. Its value depends on two factors: the speed of the armature, and the field flux. For the e.m.f. developed in any conductor varies directly as the flux density, the speed, the length of the conductor, and its arrangement with respect to the field and the direction of motion. Where several conductors are connected together, the e.m.f. also depends on the number of them and their arrangement. In the case of an armature these factors are fixed for a particular design, and may be included in a general constant. We may therefore write:

$$E_c = k\Phi n \tag{1}$$

where E_c is the counter (or direct) e.m.f. developed by an armature, k is a constant depending on the design of the winding, Φ is the field flux cut by the conductors and n is the speed of revolution. This equation may also be written

$$n = \frac{E_c}{k\Phi} \tag{1a}$$

or, in other words, the speed of a motor varies directly with the counter e.m.f. and inversely with the field flux.

Since the counter e.m.f., E_c, may be represented in terms of the impressed potential, or

$$E_c = E - Ir \tag{2}$$

where E is the impressed e.m.f., I the armature current, and r the resistance through which that current has to pass, equation (1a) may be rewritten

$$n = \frac{E - Ir}{k\Phi} \tag{3}$$

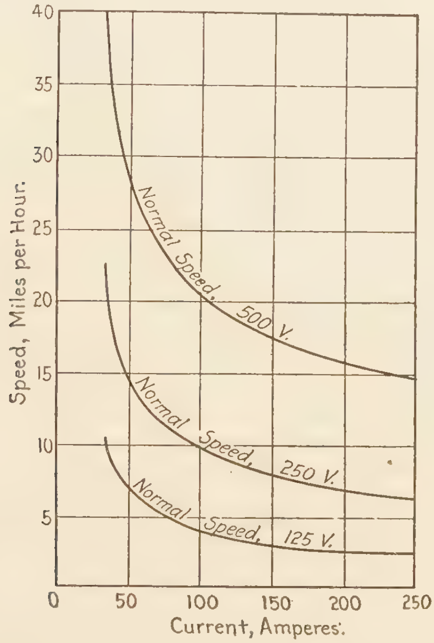


FIG. 20.—Speed curves for series motor with reduced potentials.

Consider any definite value of current, I_1. In the series motor this determines both the IR drop and the field flux, Φ. For various values of applied e.m.f., E_1, E_2, the speed may be found by direct proportion.

$$\frac{n_1}{n_2} = \frac{\dfrac{E_1 - I_1r}{k\,\Phi}}{\dfrac{E_2 - I_1r}{k\Phi}} \tag{4}$$

whence

$$n_2 = \frac{E_2 - I_1r}{E_1 - I_1\,r}\,n_1 \tag{4a}$$

This latter expression (4a) may be conveniently used for determining the speed of the motor when any potential other

than normal is impressed on its terminals. The curves of speed for the 56 kw. motor shown in Fig. 19 are redrawn in Fig. 20 at one-half potential (250 volts) and at one-fourth potential (125 volts). It may be seen from these curves that the speed is slightly less than half its normal value when the potential is reduced to one-half, and somewhat less than one-fourth the normal value when the potential is reduced to one-fourth. This is because the IR drop is a larger proportion of the total, the lower the impressed e.m.f.

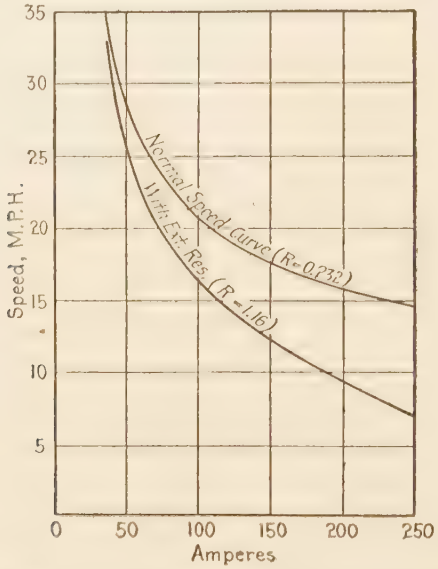


Fig. 21.—Speed curve for series motor with external resistance.

Variation of Speed with Resistance.—The other method of changing the speed by variation in potential is by the insertion of resistance in series with the motor. Its action may be determined by application of the method of equation (3), as shown by the following relation:

$$n_2 = \frac{E_1 - I_1(R + r)}{E_1 - I_1 r} n_1 \tag{5}$$

where n_1 is the normal speed at current I_1, n_2 the speed with an external resistance R introduced into the circuit, and the other values as before. In Fig. 21 is shown the speed curve for the motor of Fig. 19 with an external resistance of four times the motor

resistance added in series with it. It may be noted that the effect of this added resistance is quite small at light loads; but at heavy loads the speed is reduced until the motor is brought to a standstill. In order to obtain the same speed reduction at light loads the external resistance would need to be considerably greater.

Torque Characteristic.—It is also necessary to determine the effect of the above changes on the torque characteristic of the motor. The production of torque depends on the fundamental principle that a conductor carrying a current tends to be pushed sidewise out of any magnetic field in which it is situated. The value of this push varies directly with the current, with the flux density, and with the length of the armature conductors and their number and arrangement. For any particular motor they are permanently arranged, so that we have

$$D = k\Phi I \tag{6}$$

where D is the torque produced by the motor, k the winding constant, Φ the field flux, and I the current through armature and field. It may be seen at once that for a given value of current, the torque of the series motor is fixed, since the armature current also determines the field strength. Changes in potential have no effect on the torque characteristic of the series motor, and only serve to vary the speed at which any torque is produced.[1]

Variation of Field Strength.—In certain cases it may be found desirable to vary the field strength of the series motor. Since the field and armature draw their current through the same series circuit, it is necessary to divert a portion of it from the field winding or to actually reduce the number of turns on the coils, in order to diminish the flux. Either of these methods may be used in practice, as is explained in Chapter V. The two methods have the same effect on the characteristic performance.

Referring to equation (1*a*), it may be seen that the speed of a motor varies inversely with the field flux. This latter depends on the field current; but the relation is not a direct one. The magnetic circuit is made up of a number of materials with

[1] A small change in losses and in the magnetic relations will cause a slight difference in the torque produced under different conditions, but these changes are so small as to have little effect on the general form and value of the torque characteristic.

different magnetic characteristics and widely varying area of cross-section, so that the flux densities are quite different in various parts of the circuit. The ability of a material to carry flux depends on its permeability, and this varies widely with different values of magnetizing force and with the physical and chemical composition of the material. To determine the relation between the magnetizing force and the flux produced by it would necessitate taking the saturation curve of the machine. In the series motor, however, there is a method for determining *relative* values of flux from the performance curves. Equation

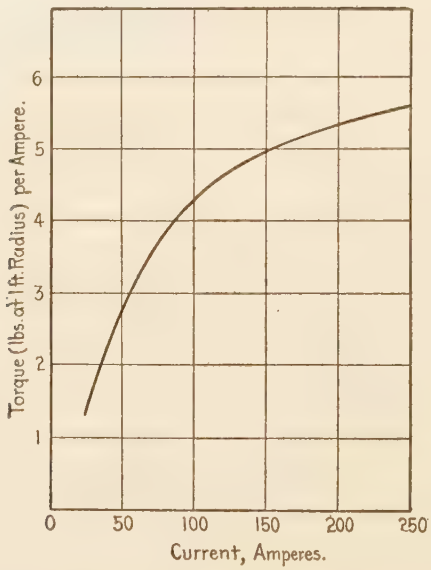


FIG. 22.—Flux curve for series motor.

The torque (or approximately the tractive effort) per ampere is a direct measure of the field flux in the series motor.

(6) gives the relation between torque, flux and current. If the torque and current are known (as for example, they are given in the curves of Fig. 19) a result may be obtained proportional to the values of flux:

$$\frac{D}{I} = k\Phi \qquad (7)$$

A curve plotted between torque per ampere and amperes (Fig. 22) will then represent the variation in flux with magnetizing

force. This relation only holds true in the case of motors whose field current is the same as or varies directly with the load current. If the field flux of a motor remain constant, as in the shunt motor, the torque varies directly with the load current, according to equation (6).

To determine the performance of a motor whose field strength has been changed from the normal value, the torque should be taken corresponding to the normal field strength, and its variation found from the ratio of values of field flux. If the armature current is the same in both cases, the torque will be in direct proportion to the flux. That is:

$$\frac{D_2}{D_1} = \frac{\Phi_2}{\Phi_1} \tag{8}$$

where D_1 and D_2 are values of torque corresponding to normal field flux Φ_1 and changed field flux Φ_2 respectively. We may then write

$$D_2 = \frac{\Phi_2}{\Phi_1} D_1 \tag{8a}$$

Since only the relative values of flux are needed, they may be found from the values of torque per ampere, as indicated in equation (7).

The effect on the speed of weakening the field may be seen from equation (3). The speed will vary inversely with the flux, so that for a decrease in flux the speed will be correspondingly greater. If n_1 be the speed with normal field flux, and n_2 the speed with changed field flux, then we have

$$\frac{n_2}{n_1} = \frac{\Phi_1}{\Phi_2} \tag{9}$$

where n_1 and n_2 are the values of speed corresponding to normal field flux Φ_1 and changed field flux Φ_2 respectively. From this we may write

$$n_2 = \frac{\Phi_1}{\Phi_2} n_1 \tag{10}$$

As with the torque, only relative values of the flux, which may be found from equation (7), are needed for the solution of the equation.

The effect on the characteristic curves of the series motor of reducing the field ampere turns to one-half the normal value is shown in Fig. 23. It should be noted that although the magneto-

motive force has been reduced to one-half, the flux is not lowered in anything like the same proportion, and the curves are not so widely different as might be anticipated.

Reduction of field ampere turns was used for controlling the performance of series motors in the early days of electric railways, but was abandoned on account of the increased tendency to sparking with the weak field. Modern designs of railway motors, using interpole construction, have made possible a return to the early method of control. It is especially advantageous for

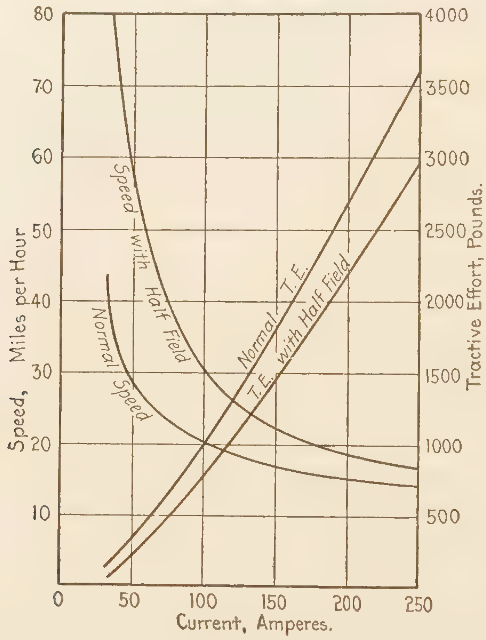


FIG. 23.—Characteristic curves of series motor with half field.

trains which have to operate at slow schedule speed with rapid acceleration for a portion of the run, and for the remainder operate at high schedule speed with few stops.

Losses in the Series Motor.—The losses which occur in the series motor, while of the same character as for any electric machine, differ in that the speed and the flux density both vary with the armature current. None of the losses are constant, but all change with the load. They may be classified as follows:

Resistance losses (copper losses)
- Armature I^2R
- Field I^2R
- Compensating (interpole) winding I^2R
- Brush loss

Iron losses
- Hysteresis
- Eddy currents

Mechanical losses
- Bearing friction
- Brush friction
- Windage.

Copper loss, being the product of the current squared and the resistance, is readily found for the series motor. The windings being all in series, the total resistance of the motor may be taken and the entire loss calculated at once. The only precaution is to remember that when the field is weakened either by reducing the number of turns, or by shunting the winding, the resistance is thereby lessened.

Brush loss is a function of the current through the brush and the drop of potential in it and in the contact between it and the commutator. This drop is largely independent of the current, being a definite amount at no load and increasing at a lower rate than in proportion thereto. The loss may be determined with various degrees of accuracy by the application of empirical formulæ to be found in electrical handbooks.

Iron loss consists of two distinct components: hysteresis loss and eddy currents. The former varies approximately as the 1.6 power of the flux density, and directly as the frequency; the latter as the square of the flux density and as the square of the speed. Since the speed decreases as the current and flux increase, the variation of iron loss with load is quite involved. It is usually determined for different current values at various potentials, as shown in Fig. 24. Ordinarily the determination of iron loss is made experimentally, and it is not readily possible to formulate an equation expressing the theoretical conditions of its variation.

The mechanical losses depend only on the speed of the machine. Brush friction varies directly as the speed, and bearing friction and windage as a power of the speed between the first and second. Their separation is difficult, and is not ordinarily

attempted. The total value of these losses is quite small unless the armature is specially constructed to circulate air through the windings for cooling.

Efficiency of the Series Motor.—In any machine, the efficiency is the ratio of output to input. It may also be stated as the ratio of output to output plus losses, or the ratio of input minus losses to input. Hence if any two of the quantities

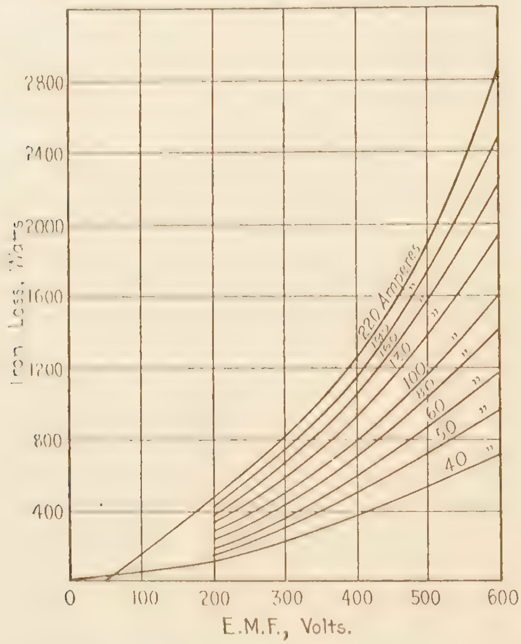


FIG. 24.—Iron loss curves for series motor.

output, input, losses or efficiency be given, the other two may be found by a simple calculation.

The efficiency of the series motor may be determined by any of the methods outlined in the last paragraph. In testing series motors, it is difficult and somewhat unsatisfactory to load them with a prony brake, as is necessary to determine efficiency by the input output method. Ordinarily the separate losses are obtained, and the performance found therefrom. For methods of calculating efficiency from losses, reference may be made to any text-book on electrical testing.

Alternating-Current Commutator Motors.—For many years attempts were made to produce motors which would operate

satisfactorily on single-phase circuits, and have characteristics suitable for railway purposes. When the alternating-current system of transmission was first brought out, motors were designed which were practically the same as the direct-current series motor. None of them was successful, since an incorrect understanding of the nature of iron loss led to the use of a solid iron structure for carrying the alternating magnetic flux. In 1902 a new type of single-phase motor was announced, which was the exact counterpart of the direct-current series motor, modified for use on alternating current by having a number of special features. In order to understand the operation of this type of motor, it will be well to trace its development from the direct-current machine.

Consider a motor operating on direct current, the field and armature being in series. If, for any reason, the current through the motor is reversed, there will be no permanent result whatever on the operation. This can be repeated as often as desired, provided it is not done more than a few times a minute. In case an attempt is made to reverse the motor too frequently, several effects are to be observed: (1) the amount of current that can be forced through its circuits will be reduced, owing to the inductance of the field windings; (2) due to this inductance, the current will lag behind the electromotive force; (3) the iron in the magnetic circuit will heat up on account of the hysteresis and eddy currents caused by the variable flux; (4) there will be severe sparking at the commutator.

It is possible to reduce the iron loss to a reasonable amount by using a good grade of electrical steel and by lamination of the metal. This is one of the first requirements of any good alternating-current motor. The inductance of the field can be lessened by cutting down the number of field turns. A considerable reduction may be made in the field ampere turns without a great diminution in the flux, since in modern direct-current motors the iron is worked at a high degree of saturation (see Fig. 22). This will reduce the inductance of the field winding, and hence diminish the lag of the motor current. The power factor can be still further improved by the insertion in the circuit of compensating coils, of the general nature of an interpole winding, with a number of ampere turns sufficient to neutralize the magnetomotive force of the armature. This will both tend to lessen the reactance and to improve commutation.

The use of these devices will in some cases produce a motor which may operate on frequencies up to about 25 cycles. In general, however, additional means must be taken to reduce the sparking to a point where it is not objectionable.

Reference to Fig. 25 will show the reasons for the excessive sparking of the single-phase motor. Consider an armature rotating in the field produced by current drawn from the line through the field winding. Whether the flux be constant or not, there will be an e.m.f. developed in the armature, its maximum value per turn being induced in the conductors directly under the poles. The maximum total appears at the brushes *B*, *B*. If the flux be varying in value (*i.e.*, alternating) there will be an e.m.f. produced due to the change in flux, which will have its maximum per turn in the conductors between the poles, and its total maximum at the brushes *A*, *A*. It may be seen that these two e.m.f.'s are entirely independent, the former, which we may call the "speed e.m.f.," depending on the mechanical rate of cutting the flux with the armature conductors, due to the speed of rotation; while the latter, which may be termed the "transformer e.m.f.," depends on the rate of change of the field flux caused by the cyclic variation in the magnetizing current.

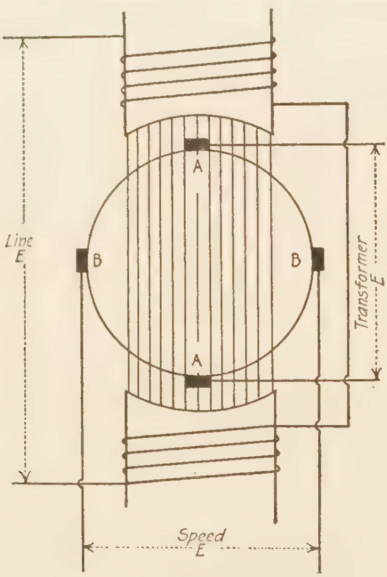


FIG. 25.—Single-phase series motor.

To operate as a normal series motor, the speed e.m.f. is the one which must be commutated, and the transformer e.m.f. must be entirely disregarded. The brushes should therefore be placed in the positions *B*, *B*. It is evident that the turns which are short-circuited by the brushes are the very ones which are generating the maximum e.m.f. due to transformer action, and there is a tendency toward severe sparking, even when the distortion of the field due to the cross ampere turns of the armature has been entirely removed by a suitable interpole or

compensating winding. Reducing the number of armature turns per commutator bar will diminish the current in the short-circuit, but not as a rule to a satisfactory value. An additional method which has been employed by one of the large manufacturers in this country is to introduce between each commutator bar and the armature winding, a fixed resistance of proper amount, sufficient to limit the current in the short-circuited coil to a safe value. The action of such resistance may be seen in Fig. 26. It will be noticed that only those resistance leads which connect to the coils undergoing commutation are in circuit, and that the ones carrying current are in parallel with each other, so that if the brush covers several bars, the resistance inserted in the path of the main current can be in-

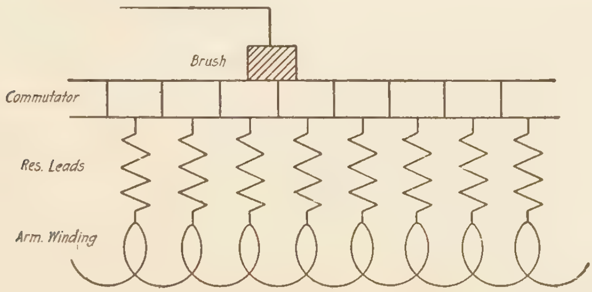


FIG. 26.—Use of resistance leads in single-phase motor.

considerable, and yet the resistance in the local short-circuit may be sufficient to reduce the sparking materially. The proper proportioning of these resistance leads is a question of considerable importance in making a successful single-phase motor of the series type.

Frequencies for Single-Phase Motors.—The general theory of the single-phase series motor, as developed above, would indicate that its performance will be better the lower the frequency. This leads to the logical conclusion that the best number of cycles is zero, or in other words, that the perfomance of the machine is best on direct current. While this is not strictly true, it does apply to a certain extent; and it is possible to operate the same motor both on alternating- and direct-current circuits. The highest frequency which can be used for a particular machine depends on the reactance of the windings, the iron losses, and the commutation. All these quantities vary as functions of

the number of cycles. Commercial designs of single-phase series motors have been made to operate on circuits up to 25 cycles per second; but the limitations make it exceedingly difficult to produce motors of this type for higher frequencies. When designed for operation on a 25-cycle circuit, the series motor will weigh from 10 per cent. to 25 per cent. more than a machine of equal rating for direct current.

The auxiliary equipment, such as transformers and regulators, shows an increase of capacity at the higher frequencies. This tends to offset the gains made in the motor performance when the number of cycles is reduced. Manufacturers of single-phase equipment consider that the best compromise is the use of 15 to 17 cycles, which gives a marked increase in motor capacity over that at 25 cycles, while at the same time the auxiliary equipment is not excessively heavy. The electrical performance of the series motor at this lower frequency is considerably improved.

While the reduction in frequency is entirely beneficial to the series motor, the effect on the repulsion motor is not so good. As is shown in the following paragraphs, motors of the repulsion type have some of the characteristics of the transformer, and a reduction in frequency therefore tends to increase the weight somewhat. The commutation is also better at high frequencies, since the speed e.m.f. is disregarded to a considerable extent and the transformer e.m.f. commutated. The general characteristics of the repulsion motor are not, however, so good for traction as those of the series type.

Variations of the Alternating-Current Series Motor.—Due to the inductive effects of alternating currents, the arrangement of circuits in the single-phase motor is open to considerable variation without interfering with the performance to any marked extent. Leaving out of consideration the plain series motor, consisting of only an armature and a set of field coils, and which is not an operative success, we can have three different types of series motor.

Fig. 27 shows the ordinary type of series motor, described above, which is commonly known as the "conductively compensated" type. In this, as in the direct-current series motor with interpoles, all the windings are in series.

Since the armature winding is a source of magnetic flux, the current for the compensating coils may be obtained by trans-

former action from this flux, without connection to the main circuit. Such a motor, known as the "inductively compensated" type, is shown diagrammatically in Fig. 28.

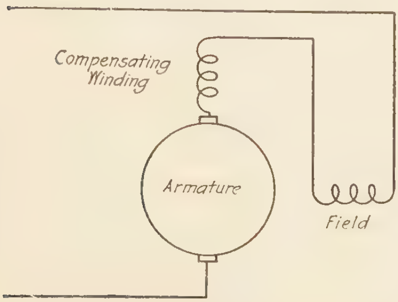


FIG. 27.—Conductively compensated single-phase series motor.

In this machine the armature, compensating winding and field are all in series. It will operate either on alternating or on direct current.

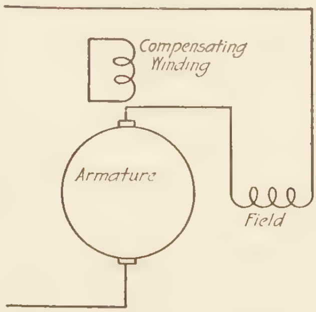


FIG. 28.—Inductively compensated single-phase series motor.

In this machine the compensating winding is short-circuited, the current in it being produced by induction from the armature.

It is possible to go a step further, and let the armature flux excite both the compensating coil and the main field, as shown in Fig. 29, which illustrates the "induction series" motor. Of the three types, the former two are used in practice, the conductively

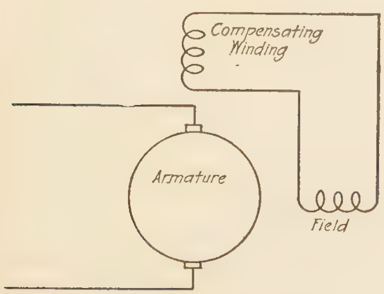


FIG. 29.—Induction series motor.

In this machine both the field and the compensating winding are short-circuited, the current in them being induced from the armature, which is connected to the line.

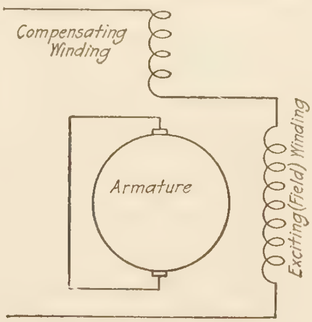


FIG. 30.—Atkinson repulsion motor.

This machine is electrically the reverse of the induction series motor, the armature being short-circuited and the other windings connected to the line.

compensated motor finding its use principally where it is necessary to operate the same machine on both alternating and direct current.

Repulsion Motor.—As it is possible to make either coil of a transformer the primary, so the connections of the induction series motor may be reversed to make the field and compensating windings the primary, and the armature the secondary, circuit. In this form, shown in Fig. 30, the machine is known as the Atkinson repulsion motor. It may also be considered as a development of the plain repulsion motor, which is shown in Fig. 31. In the latter type use is made of the transformer e.m.f., which is entirely disregarded in the series motor. The brushes are placed at an angle with the field, so as to utilize portions of both the transformer e.m.f. and of the speed e.m.f. in order to obtain variable speed characteristics. The repulsion motor has a great advantage over the series motor, in that the primary, being the stationary member, can be connected to the supply circuit without movable contacts, as when the current must be led through a commutator; the primary can therefore be wound for relatively high potentials. It is also possible, since the coils generating the maximum transformer e.m.f. are not short-circuited, to operate it on somewhat higher frequencies than with the series motor. At starting the short-circuit current is lower than in the series motor, and the necessity of using resistance leads much less, so that by careful design they may be omitted. But in general the characteristics of the repulsion motor are not so well suited for railway work as are those of the series motor, and it never has become popular for this class of service.

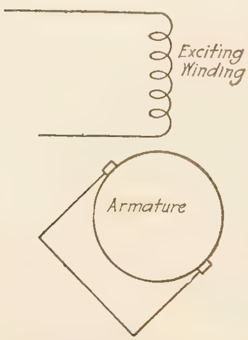


FIG. 31.—Plain repulsion motor.

This differs from the motor shown in Fig. 30 in that the compensating and the exciting windings are combined. For that reason the brushes are placed at an angle with the field.

Compensated Repulsion Motor.—A modification of the repulsion motor, known as the compensated repulsion motor, or the Latour–Winter–Eichberg motor, has been developed to obtain the advantages of both the series and the repulsion types. This motor (Fig. 32), has two separate sets of brushes, one set short-circuited, the other connected in series with the field. In this way it combines the characteristics of both the series and the repulsion types. It has been used to some extent in electrification work in Europe, but has not been applied in the United States.

Performance of the Alternating-Current Series Motor.—Referring to the vector diagram of the e.m.f.'s in the series motor, Fig. 33, it may be seen that the total potential at the motor terminals is divided into three components: the drop *OB* across the field, the drop *BD* across the armature, and the speed e.m.f. *DE*. For any given current value, the two drops are constant, no matter what the speed.[1] If the motor is at a standstill, these drops will constitute the entire potential *OD* at the motor terminals. As the speed of the motor is increased to give a counter e.m.f. *DE*, it must be accompanied by an increase in the terminal potential, as given by the vector *OE*. Since the speed e.m.f. must be in phase with the current, while the armature and field drops are always ahead of it, it may be seen that an increase of speed will improve the power factor of the motor. By keeping the reactances in the circuit down to reasonable values, the normal operating power factor of the motor may be made very satisfactory; that is, it can be made as good as or better than the power factor of induction motors of similar capacity.

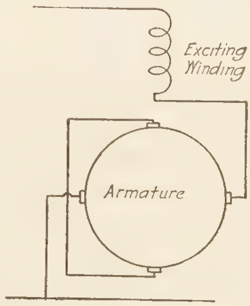


FIG. 32.—Compensated repulsion motor.

This machine combines the characteristics of the series motor, Fig. 27, with those of the repulsion motor, Fig. 31.

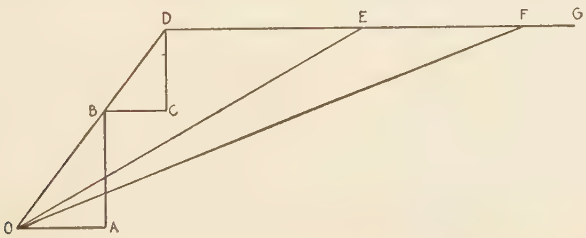


FIG. 33.—E. m. f. and current relations in single-phase series motor.

The characteristics of a typical single-phase series motor are shown in Fig. 34. The speed curve is more dropping than with the direct-current series motor, due to the lower saturation of the magnetic circuit. For the same reason the tractive effort

[1] The armature and field drops are each equal to the product of the current by the impedance of the circuit. Since the frequency is constant, the reactances are practically constant in any particular machine. They will be changed slightly by variations in iron loss at different speeds.

approximates more nearly the parabolic form than in the commercial direct-current series motor. The power factor approaches unity at zero current, and decreases from this value almost uniformly in proportion to the load.

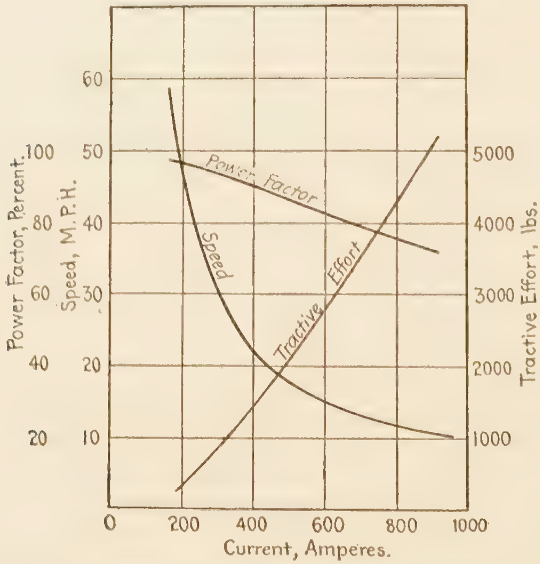


FIG. 34.—Characteristics of single-phase series motor.

Note that the speed curve is more drooping than for the normal direct-current series motor, on account of the lower saturation in the magnetic field.

Variation of Single-Phase Motor Characteristics.—The characteristics of the alternating-current series motor may be varied in much the same manner as with the direct-current series motor. The three methods which may be used are:

1. Variation of terminal potential.
2. Insertion of series resistance.
3. Variation of field strength independently of armature strength.

The first method is more readily applicable than with the direct-current motor, since alternating e.m.f.'s of any desired value may be secured with the aid of a stationary transformer. The ease in obtaining change of motor potential makes the other methods of control unnecessary. The use of series resistance is uneconomical, and persists with direct-current motors only as a matter of necessity. The variation of field flux in the alternating-

current motor is undesirable, since to make a good commercial machine the flux has to be cut down normally to a minimum, and further reduction is unwise.

When the terminal e.m.f. is lowered, it is evident that the power factor will be reduced, since the quadrature component of potential remains about constant, while that in phase is diminished, due to the lessened speed. As with the direct-current series motor, a reduction in potential does not change the torque to any great degree. Since the potential in an alternating-current circuit may be varied at will either by means of a stationary transformer with a number of taps on the secondary, or by a transformer with a rotatable secondary (induction regulator), it is easy to obtain a wide variation in potential without the need for re-connecting the motors, as in a series-parallel combination, and without the loss inherent to the use of resistance in the armature circuit.

Commutation in Single-Phase Motors.—A comparison of the circuits of the series and the repulsion motors makes it evident that the series motor has its brushes placed in such a position that the transformer e.m.f. is short-circuited at starting; while the repulsion motor short-circuits the speed e.m.f. The repulsion motor should therefore have better commutation when starting, while the performance of the series motor in this respect will be superior at speeds above synchronism. At synchronous speed the e.m.f. developed by transformer action is equal to that produced by the conductors of the armature cutting the field flux, so that the potential is uniform at all points around the commutator. At this speed the sparking will be the same no matter where the brushes are placed. The various methods used for improving the commutation make the series motor satisfactory at starting; but so far the repulsion motor has not given good results as regards sparking at speeds much above synchronism. Since the power factor of the series motor is better as the speed increases, it has a considerable advantage in performance for high-speed work.

The Polyphase Induction Motor.—The polyphase induction motor is so well known, and its characteristics have been so fully described, that no general treatment will be entered into here. It is sufficient to understand that the motor possesses performance characteristics similar to those of the shunt motor, as shown in Fig. 35. If the machine is well designed, the drop in speed from

no load to full load is but a small amount, rarely over 5 per cent. The normal speed–torque curve of such a motor is given a "Notch 7." It will be noticed that the effort available at starting is considerably less than the maximum running torque. It may further be shown that to produce this starting torque requires a relatively large current, and at a low power factor. If the secondary resistance of the motor be greater, a curve such as "Notch 6" may be obtained. Here the starting torque is increased; but in order to accomplish this result, the efficiency over the entire working range has to be sacrificed. By considerably increasing the secondary resistance, as by the use of

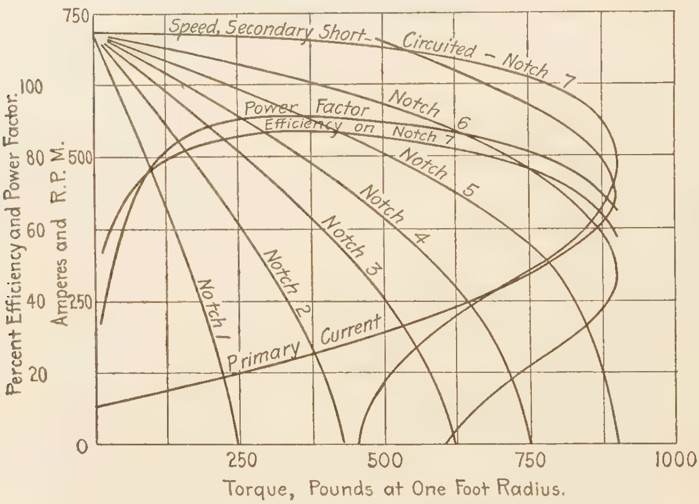


FIG. 35.—Characteristics of polyphase induction motor.

external resistors, the starting torque may be increased to the maximum possible value, as at "Notch 5;" or, if it be desired to reduce the starting current further, and the maximum torque is not needed at starting, additional resistance will give curves such as Notches 1, 2, etc. In all of these cases, however, the efficiency is very much reduced, being in no case as great as the speed in per cent. of synchronism. It is evident, then, that to get efficient operation, the resistance must be inserted only during the starting period, it being gradually cut out of the circuit as the speed increases, until the motor is operating with short-circuited secondary. With this connection the motor will operate at practically constant speed.

Another method of reducing the speed at starting is to lower the potential applied to the terminals. Since the motor receives its magnetizing current and the working current in the same winding, any reduction of the potential will decrease the field strength as well as the load current. In normal induction motors, the field iron is practically unsaturated, so that the flux is lessened nearly in proportion to the reduction of potential. The decrease in primary potential causes a similar reduction in the secondary induced e.m.f., so that the secondary current is lessened. It follows that the torque produced at any given value of load current varies as the square of the applied potential. When the primary potential is reduced the power factor and the efficiency are also lowered, so that the performance is poor. A further effect, due to the larger proportion of losses in the motor, is that the heating at any given primary current is increased and the capacity of the motor reduced. If the induction motor is used for starting heavy trains, this method of speed control is not to be recommended; and in any case it is far inferior to the first method, by insertion of resistance in the secondary circuit.

The induction motor inherently must operate at a speed somewhat below synchronism; and we have seen that the normal curve does not fall far below this value. It is possible to change the speed of the motor if the synchronous speed can be changed; and this can be done without any great sacrifice of power factor or efficiency. There are two methods by which the synchronous speed may be altered: by variation of the frequency, and by a change in the number of poles on the primary and secondary. No variation in frequency can be expected in the supply circuit, so any change made must be in the control of the motor. This is usually done by "cascade control" or "concatenation," in which the secondary current from one induction motor is fed into the primary of another motor, the two being mechanically connected together so that they must run at the same speed. This will be described more in detail in connection with methods of control.

The number of poles on an induction motor may be changed much more readily than on a direct-current motor, since the field is usually constructed with a distributed winding. The inclusion of more or less coils in a group makes it possible to re-connect the winding to give two or more sets of poles with the same field coils. To get more than two sets of poles with the same coils

complicates the winding to an extent where it is not practical; so for such cases the primary and secondary parts of the motor are each supplied with two or more separate windings, in case more than two speeds in the ratio of 2 : 1 are desired. This method of speed control has been worked satisfactorily in a considerable number of European locomotives; but is too cumbersome for use with individual motor cars, especially where train operation is desirable on the multiple-unit system.

Induction Motor Performance.—Under normal conditions, the efficiency of the induction motor can be made at least as high as that of the best direct-current series motors, and with a somewhat smaller weight per unit of output. The efficiency is somewhat better than that of the single-phase series motor, being about equal to the efficiency of the direct-current series motor. The power factor is at least as low as, or often lower than, that of the single-phase motors, so that the line current required is equal to or somewhat greater than that required for the series motor. Further than this, it must be remembered that the induction motor operates only on a polyphase circuit, so that at least two trolley wires are necessary, using the track for the third conductor. If it is possible to install a rotating phase changer on the locomotive, polyphase motors may be used on a single-phase supply system. This is actually being done on one American railroad at the present time.

CHAPTER IV

RAILWAY MOTOR CONSTRUCTION

Motor Development.—Although the first experimental electric railway was built in 1835, and various inventors were from time to time developing model electric locomotives, it was not until the year 1879 that anything resembling a practical electric road was produced. From that time the improvement was rapid, and it was only a comparatively few years until the essentials of the modern electric railway had been invented and applied.

The motors used during the first or experimental period, from 1835 to 1879, were mere toys, and had no practical operating value. In the latter year, the great engineering firm of Siemens and Halske exhibited an electric locomotive designed to draw a light train of passenger cars. This train was displayed at the Berlin exposition. It marked the change from a scientific toy to a practical means of train propulsion. The Siemens locomotive was equipped with a single stationary type motor, mounted on the platform, and belted to the axle.

In the next few years a large number of inventors, both in America and in Europe, produced electric locomotives and motor cars which were more or less successful. In all of the earlier types the motors were the ordinary stationary machines, usually applied to the work without any change whatever. In some cases even arc-light generators were used as motors. It must be understood that the equipment in these early roads was exceedingly crude. This was not surprising, since the application of electrical machinery in general had just begun, and practically none of the present theory had been developed.

Early Motors.—In the early electric railways in this country the practice mentioned in the first road (that of the Siemens and Halske firm) of using a motor placed on the platform of the car or locomotive was adhered to. This was almost necessary, since the performance of the motors was so poor that it was absolutely essential to keep a close watch on the motor operation,

especially of the commutator and brushes. It was considered the best practice to shift the brushes to give good commutation; and if the car was reversed, a considerable brush displacement was called for.

With the road installed in Richmond in 1888 by Frank J. Sprague came the recognition that the railway motor is a special piece of machinery, and should be designed to perform its work in the best possible manner. In this installation the motors were hung on the car axles, and were inaccessible from the floor of the car for constant inspection and adjustment. Since these motors were designed to be reversible, it was necessary to place the brushes in the neutral position, making no allowance for shifting them to obtain good commutation. This practice has

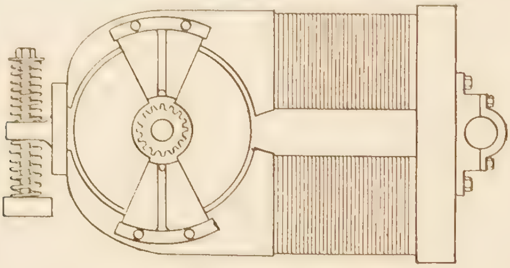


Fig. 36.—Sprague motor.

This is the type of motor which was used on the Richmond road in 1888. Several different forms were used, but the general appearance of all was quite similar.

persisted to the present time, and the design of modern motors has always been made with this feature as a necessary detail.

The early motors were all bipolar, following the stationary practice of that time. It was not until about ten years after the first electric railways were operated that it was considered more economical to use multipolar designs, in order to get better distribution of the active material and to obtain improved performance. When it was found possible to build multipolar railway motors, an attempt was made to use a comparatively large number of poles. This arrangement was also abandoned in favor of motors with four poles, which number has become standard for all direct-current railway motors of the ordinary types.

The first railway motors, being a direct adaptation of the stationary types, were entirely open. While this type of machine had better facilities for getting rid of the heat generated by the losses, the exposure of an open motor under a car, to all

sorts of dirt, mud, and water, led to grounding of the insulation, pitting of the commutators, and rapid destruction of the bearings. The logical remedy was to totally enclose the working parts of the motor, extending the field frame to make a casing around the field and armature. The first attempts of this sort did not aim at total enclosure of the working parts. While the partial enclosing did some good, there was still difficulty from splashing water and dust. The successive designs went further, until no openings whatever to the interior of the motor were left. Access to the commutator was had by means of a hand-hole with removable cover; but since by that time the commutation had been improved to a point where constant inspection was unnecessary, this caused no disadvantage.

Armature Construction.—The early armatures were of the smooth core, hand wound drum type, usually with one turn per commutator bar, with either a lap or a ring winding. Such a construction requires as many brush arms as the motor has poles. It was found that by the use of the two-circuit wave winding but two brush arms were required, irrespective of the number of poles on the motor. This was an important improvement, since it became possible to place both brush arms on the upper part of the commutator, where they could be easily inspected through the hand-hole. Better knowledge of the phenomena of commutation led to the use of slotted cores for the armatures. This was more of an advance than may appear at first, for the heavy torque required at starting had the effect of stripping the windings off the smooth cores. With the slotted type, the wires had a solid wall of iron against which to exert the push. The knowledge of commutation also made it possible to wind the armatures with more than one turn per commutator bar, thus making a cheaper and more rigid construction, and facilitating repairs.

These changes in armature construction were coincident with improvements in the brushes and brush rigging. The early machines used brushes of leaf copper, such as are sometimes employed at the present time on electrolytic machines. The use of brushes of this type, with inherently low resistance, made a small number of turns between bars necessary to prevent excessive sparking. In the history of the Richmond road, brushes of solid bronze were used at one period. Replacement

of all these types of brush with those of carbon made possible the changes in armature design noted above.

Armature Speeds.—In nearly all of the pioneer designs of railway motors, the armatures were of large diameter. This construction was adopted to get the necessary high peripheral speed without having an extremely great angular velocity. Even with the large armatures the speeds were excessive in many instances. The use of multipolar motors made possible a lower peripheral speed, and, at the same time, a reduction in speed of rotation. This effect was aided by lengthening the core somewhat parallel to the shaft. The large diameter armature, especially when rotating at a high speed, possessed a great deal of inertia. We have already seen that the inertia of the rotating parts of the equipment is a comparatively important part of the total for a moving car. The still larger amount of inertia caused the consumption of additional energy, and considerable extra brake wear, besides increasing the time for stopping the cars.

In most of the early motors, the armature speeds were so high that single-reduction gears could not be used, and it was necessary to have back-geared or double-reduction motors. This caused an extra loss, and an added complication that did not seem warranted. The slower armature speeds obtained in the later designs brought at the same time the single-reduction gearing which has persisted to the present time except for certain large locomotive motors.

Field Frames.—Motors of the old horseshoe type were almost invariably made with field yokes of wrought iron. While this material has excellent electrical properties, it is entirely too expensive for use on a large scale, as in railway motors. The alternative material which was developed in the early history of electric motors is cast iron. This is much cheaper, but requires approximately twice the weight for the same field strength. On the other hand, it lends itself better to the totally enclosed designs which were coming into vogue at the time it was introduced. Cast iron, in its turn, was found too heavy, and in some cases not strong enough. It was gradually superseded by cast steel, which has been the accepted material for railway motor frames for over fifteen years. Cast steel is more expensive per unit of weight than cast iron; but its superior magnetic properties

allow the manufacture of a frame weighing about half that for a cast-iron one, and at approximately the same cost.

If there is a sufficient demand for motors of a certain type, it is possible that cast steel may in its turn be superseded by frames of rolled and pressed open-hearth steel. Although the first cost of a pressed-steel frame is exceedingly high, the manufacture of large quantities of a certain single design will make it an active competitor of the cast steel. One design has already been made using pressed steel, and which is superior in many ways to the ordinary type of cast-steel motor.

The changes outlined above mark the development of the railway motor from a crude device, upon which little reliance could be placed, to one that can be used without difficulty, and will perform its work satisfactorily under the severe conditions of service inherent to railway operation. The structural development outlined was carried along with an improvement of construction details both electrical and mechanical. The result is an increase in efficiency from quite low values, to fairly high ones over the entire operating range. In a railway system, efficiency of the traction motor is but a small item; but the saving in cost due to the increase in efficiency is worth considerable to the railway operator, since it has come with other improvements of a desirable nature.

Modern Direct-Current Railway Motors.—The development we have just traced has been entirely in the direct-current series motor. The greater part of it took place prior to the year 1893; since that time the changes have been more in the nature of minor refinements than in radical developments.

Modern Motor Frames.—The frames of modern motors are made of cast steel, and include the magnetic circuit of the field, with the protecting casing. There are two types of frame in general use—solid and split. The split frames are the earlier development. It was formerly the universal practice to inspect the motors without removing them from the car axles. This is done in one of two ways. The motor is split in a horizontal plane through the shaft in such a manner that the lower half can be dropped down, thus permitting inspection from a pit beneath the track; or else the upper half can be raised, allowing inspection on the shop floor after the truck has been run out from under the car. This latter method was used only on a few

of the largest systems, the former being much more widely employed.

With the refinements which have been made in modern motors, the need for inspection has diminished, so that it is possible to make a far greater mileage between overhaulings of the motors than previously. This has made possible the use of motors with solid frames, the armatures being removed from the end. This latter construction is more rigid and somewhat cheaper; but it makes it impossible to remove an armature unless the entire motor is first taken off the truck. To determine the clearance between the armature and poles, it is customary to have small hand-holes for inspection in the lower portion of the motor case.

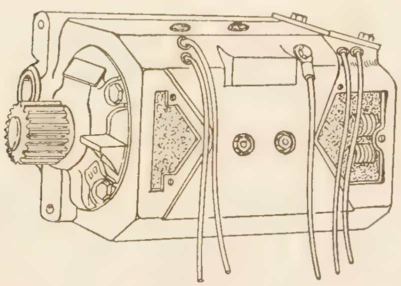


Fig. 37.—Modern direct-current railway motor.

This is the solid-frame type of motor. The armature is removed by taking off the end-bell after the motor has been removed from the car. The axle gear and the gear case are not shown.

The choice of solid or split frames depends largely on the shop equipment available for handling the motors. In some small shops it is quite difficult to remove and replace the armatures of solid-frame motors; but in the larger shops, especially those equipped with cranes, the employment of this type has proved entirely saisfactory; and their use seems to be growing at the present time.

In the first designs of railway motors, the poles were made integral with the main horseshoe forgings for the field. This was fairly successful, since a high-grade magnetic material of practically uniform permeability was used. The first machines with cast-iron frames had the poles cast in the frames. This design was not successful, since neither the control over the quality of the metal, nor the dimensions of the poles, was complete. In a few types, an attempt was made to correct this trouble by building up poles of laminated steel, and casting them into the motor frame. While this was an improvement, it did not meet all the demands of a satisfactory pole structure. In all modern motors the poles are made of steel laminations, built up and riveted together. They are fastened into the field frame with bolts, and

are so designed that they may be removed without taking the armature out of the case.

The use of the laminated pole makes it possible to shape the pole tips to aid commutation, and they can be properly spaced in the frame to ensure correct alignment. This feature, although perhaps not fully appreciated, is one of the factors in the splendid performance of modern direct-current motors.

Use of Interpoles.—Within the past few years the use of interpoles has become quite general. Of all types of commutator electric motors, the series machine has the least inherent tendency to spark, since the field strength automatically increases with the armature current. The sudden and heavy overloads, however, make the very best commutation a necessity for continued successful operation. In all cases where constant attention cannot be given the commutator, the destructive results of sparking are cumulative; and even though the sparking of well-designed non-interpole railway motors was formerly considered negligible, the wear of both commutator and brushes is considerable. The use of interpoles has reduced sparking to a point where it is practically absent; and with its decrease a great gain has been realized in the life of commutators and brushes.

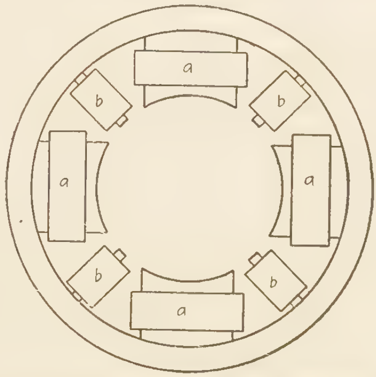


Fig. 38.—Arrangement of interpoles. The main poles, *a*, and the interpoles, *b*, have windings which are placed in series with the armature. Usually the main field winding is reversed to change the direction of rotation.

In form the interpoles are practically the same as those for stationary direct-current machinery. The turns are, so far as possible, concentrated near the armature surface, to increase their effectiveness. The supporting cores are of steel, bolted into the field frame between the main poles. The interpole coils are connected directly in series with the armature and field windings, and are arranged so that they may be reversed along with the armature, in order that the current through the commutating coils may be in the proper direction to assist the commutation and not hinder it.

Modern Armature Construction.—The armatures of modern motors are invariably of the slotted drum type, and are wound with two complete coils per slot. The early armatures of this class were designed with a comparatively large number of small slots, each with one or two single coils in it. This practice causes weak, narrow teeth, and is wasteful of space, since the major coil insulation must necessarily be of a definite thickness whether one or a number of separate coils are assembled together. Incidentally the cost of punching the iron with a large number of teeth is greater, and the commutation is poorer. Modern practice is to include from three to five single coils in each complete coil, so that the total number of slots is considerably less than in the early armatures, even though the number of commutator bars has been increased.

In some motors the armature punchings are assembled directly on the shaft, and in others they are mounted on a spider of cast iron. In the larger machines the use of the spider is universal. Its employment depends on the amount of iron which needs to be left back of the teeth for carrying the flux, and on the arrangements made for ventilation.

Armature windings of direct-current railway motors are almost invariably of the two-circuit type. The use of two-circuit windings, as has already been stated, results in the need for only two brush arms, no matter how many poles the motor has. On the other hand, if the current capacity is large, a brush-arm can be supplied for each pole of the motor, thus making possible a short commutator. The maximum currents to be handled with direct-current motors are usually well within the limits of the two-circuit winding.

Armature coils are made of wire only in the small sizes. For the larger motors, strap-wound coils are the universal practice. The strap gives a better space-factor—*i.e.*, the proportion of the slot occupied by copper is greater, and that taken up by insulation is less. Generally, the individual armature coils are wound complete in one piece; but in some types the coils are separated into two parts, and are connected together at the back end of the armature. This makes replacement of damaged coils easier, but increases the number of soldered joints.

Commutator Construction.—Modern commutators are generally built of rolled or drop-forged copper. Uniformity of the surface has much to do with long life of the commutator and

brushes in service. Another factor is the material employed for insulation between bars. Although a number of materials have been used, the only one which has been satisfactory is mica. At the present time it is exceedingly difficult to obtain mica of uniform quality, and in consequence the practice has been adopted of using insulation built up from small sheets of this material held together with some form of binder, such as shellac. To get good service from a commutator, the insulation and the copper must wear down at the same rate. If the mica is too soft, it will wear away faster than the copper, and leave low spots at the edges of the bars. On the contrary, if the mica is too hard, it will not wear away as rapidly as the copper. The result will be that the brushes will have a tendency to jump away from the surface of the commutator, causing sparking and flashing which will conduce to further pitting and wearing down of the copper, until turning is necessary. Practically all the mica which is available for commutator insulation at the present day is harder than the copper surface, giving the latter effect. The remedy for this is the practice, which is being quite generally adopted, of "undercutting" the mica, or removing it to a depth of about 1/16 in. below the surface. This permits the brushes to bear evenly on the commutator, and allows uniform wear of the copper. With the aid of commutating poles and undercut mica the commutation of modern motors is well-nigh perfect.

Motor Lubrication.—It is in the mechanical parts of the motor that the most radical changes have been made since the beginnings of electric railway operation. In the early machines, lubrication was commonly effected with grease. Grease as a lubricant is theoretically inefficient, since it requires the bearing to overheat before acting. It has been replaced by the use of oil, carried to the rotating part by capillary attraction through the medium of wool waste, which rubs against the shaft, and thus ensures a constant supply of oil under all conditions. Both armature bearings and axle bearings are lubricated in the same manner.

Bearing Housings and Bearings.—As the early motors were of the open type, there was little difficulty in removing the armatures for inspection or for repair. When the enclosed motors became standard, provision for removing the armatures was made by splitting the frames, as already explained. With

the modern solid-frame motors, the armatures must be removed from the ends of the casing. To do this, the opening in the end of the frame must be at least as large as the diameter of the armature. The accepted method of closing this opening is to use a bearing bracket, turned to fit a bored hole in the frame, and containing the bearing and bearing housing, together with the oil receptacle. The same type of end bracket has been adopted with split-frame motors, on account of the rigid support it gives the bearing, and its excellent arrangement for oiling.

The bearings proper are made of brass or bronze, with the wearing surface of babbitt metal. This construction is good, since the use of a soft metal reduces the friction to a minimum under normal conditions; and if anything happens to melt out the babbitt, the bronze itself furnishes a good bearing to run on until the motor can be removed from the car at the end of the trip. Without such a safeguard the melting of the babbitt would cause the armature to strike the pole faces, resulting in damage to the winding and possibly destruction of the core itself.

Ventilation of Motors.—The oldest railway motors, being open, were ventilated entirely by natural circulation of the sur-

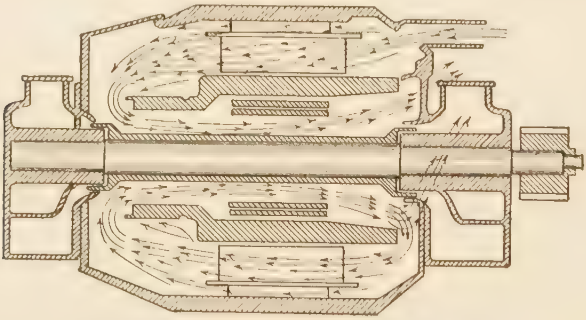


Fig. 39.—Method of forced ventilation.

The air is circulated through the motor case by means of fans carried on the armature. A number of other arrangements of air-paths are in use to obtain a passage of air through the motor case.

rounding air. With the advent of the enclosed motor, a different condition was confronted. The outside air no longer had access to the armature, commutator and field coils; but all the heat generated had to be transferred to the frame and dissipated from the outside surface of the case. The result was that the capacity of a motor of given weight was much smaller than in

the case of the corresponding open machine. But it has been found necessary, on account of the bad effects of dust and moisture, to keep the motors almost completely enclosed. A number of years ago an attempt was made to force air into the motor by means of ducts leading to the front of the car. This was not entirely successful; but it led the way to the use of fans on the motor armature, by means of which a circulation is established, drawing air in from the outside, and passing it through the motor, finally discharging it again. By this method, shown in Fig. 39, the temperature of the motor may be reduced materially for the same load, or the rating of a given motor may be increased. The result is to lighten the equipment.

In the large locomotive motors such ventilation would not be sufficient, especially since the greatest generation of heat occurs when starting. At this time the efficiency of any fan driven by the armature is least, and the cooling effect small, since the speed is low. To give an adequate supply of cooling air to such motors, they are provided with ventilating ducts, the air being furnished from an independent motor-driven blower located in the cab.

Single-Phase Commutator Motors.—In the case of single-phase motors, the field flux is alternating. A solid field structure is inadmissible, and it is necessary to provide a complete laminated core for the magnetic flux. This leads to a quite different arrangement from that of the standard direct-current motors. The field is built up of a set of punchings, which are held rigidly in a frame of cast steel that also serves as the enclosing case of the motor. The poles are made integral with the core, for it is impossible to remove them on account of the compensating winding.

The field coils of alternating-current series motors are not essentially different from those of direct-current motors, except that they have less turns. The compensating windings, instead of being concentrated, as in the direct-current interpoles, are distributed over nearly the entire pole-face. By this means the neutralizing ampere turns are placed very near the armature conductors whose inductance it is desired to oppose, and their effectiveness is increased.

On account of the compensating winding, it is not possible to split the frame; and, since the majority of single-phase motors are of comparatively large rating, and are used on roads with

adequate shop equipment, there is not a great demand for that construction. In most modern machines, the external appearance is not essentially different from that of direct-current motors of similar capacity.

The armatures of alternating-current series motors are very nearly the same as those for direct-current motors, the principal apparent difference being the greater number of commutator bars on the former. In the type manufactured in the United States, there is a difference, not readily discernible, due to the interposition of resistance leads between the armature coils and the commutator. These leads are placed in the bottoms of the slots in the smaller sizes of motors; and in the larger ones are

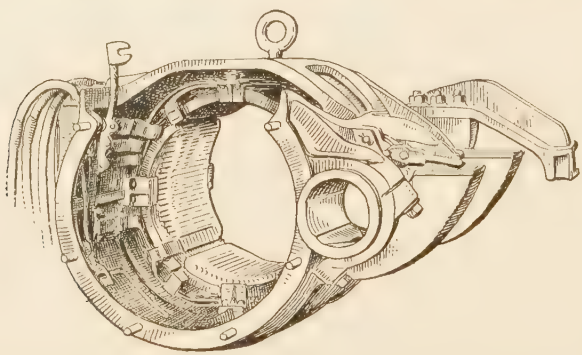


Fig. 40.—Interior of single-phase series motor.

The pole faces are slotted, and have the conductors of the compensating winding embedded in them.

placed in the core in separate slots located beneath the path of the flux. This method of construction makes repairs and replacements comparatively easy.

In distinction to the direct-current armatures, those of single-phase motors are ordinarily lap wound. Since there is a possibility of uneven distribution of the magnetic flux, due to inequalities in the air gap, it is customary to supply them with balancing rings such as are used on large generators. The use of these rings permits equalizing currents to flow in the armature, thus compensating for variations in the magnetic strength of different poles.

The use of lap-wound armatures makes obligatory the use of as many brush arms as there are poles. In order to improve the performance of the motors, there is a tendency to increase the

number of poles, which requires an additional number of brush arms. For this reason it is somewhat more difficult to maintain the brushes on single-phase motors.

None of the purely mechanical parts of the alternating-current series motors are essentially different in any particular from those of direct-current motors. In fact, the external appearance is nearly identical for the two types of machines. Since the alternating-current motors are used to a considerable extent on large locomotives, the design of individual units may lead to a material difference in appearance.

Induction Motors.—The design of induction motors for railway service calls for more radical departures from the ordinary direct-current designs than is the case with the series motor. The field or primary winding is usually placed on the stator; but it must be distributed, and resembles an armature winding. This calls for a different type of construction. The enclosing frame, however, may be made to resemble that of the direct-current motor quite closely, and the mechanical parts may be the same.

The secondary is generally made the rotor; and, for the forms ordinarily used in traction work, the winding is of the definite type, similar to that of the primary. There is this essential difference: no commutator is required, and the ends of the windings are brought out to collector rings, through which the current is led to the resistors by means of brushes. The secondary has no connection whatever with the supply circuit, and can be wound for any convenient potential. The secondary windings are nearly always made three-phase, since this allows of the minimum number of rings and brushes.

The location of the collector rings is a matter of some importance. If the size of the motor is not excessive, the rings can be located inside the frame, in a position similar to that of the commutator in a series motor. If the capacity of the motor is large, it may be difficult to find room for the collector. In some designs it is mounted inside the spider; in at least one, the leads from the winding are taken through the bearing in a duct bored in the shaft, the collector being placed outside the crank. While this may be considered an extreme design, it was necessitated by the demands made on the motor for space.

CHAPTER V

CONTROL OF RAILWAY MOTORS

Need for Control.—If an electric motor of any type, with its armature at rest, were connected directly to the line, an excessive current would flow, limited only by the impedance of the motor and the supply circuit. In case the protective devices failed to open the circuit, the torque produced would in general be so great as to slip the driving wheels; or, failing to do that, to start the train with a severe jerk. Since a fairly uniform acceleration of moderate amount is desirable, some form of control which limits the torque to a proper value is an absolute essential to satisfactory operation.

Available Methods.—There are two general methods for obtaining the desirable changes in characteristics, which are applicable to nearly all types of electric motors:

1. Variations in potential.
2. Changes in relative strength of armature and field.

For certain types of alternating-current motors, the characteristics may be varied by the following additional methods:

3. Changes in the number of poles.
4. Changes in frequency.

Change of Potential.—The effect of changes in the terminal potential is different with various types of motors. In the case of "constant field" machines, such as the direct-current shunt motor, or the alterating-current induction motor, a change of potential at the terminals varies the field or magnetizing current and hence affects the field flux. The variation in the flux corresponding to a given change in the terminal e.m.f. depends on the characteristic of the magnetic circuit; and in general is different for individual machines. If the magnetic circuit is practically unsaturated, as in most alternating-current induction motors, the torque produced by a given current varies approximately as the square of the e.m.f. In this type of motor a reduction in the terminal potential has a comparatively small effect on the speed,

that being determined principally by the frequency of the supply circuit.

In the direct-current shunt motor, a change of potential will not have quite so much effect on the torque as in the induction motor, since the field is normally saturated to some extent; but the change in torque will be considerably greater than in direct proportion to the applied potential. At the same time the speed will be varied somewhat by a change in e.m.f. These effects may be obviated by placing the field winding in a separate circuit and keeping it connected to a source of constant potential. The field flux will then remain constant, and the torque will be the same for any value of terminal e.m.f. The speed will vary practically in proportion to the applied potential.

In the series motor, a change in the terminal e.m.f. has no effect on the field flux for a given current; but the speed will vary nearly in proportion to the e.m.f. applied to the terminals (see Chapter III).

Methods of Potential Variation.—The possible methods by which the potential may be varied in railway motor control are:

1. Change of e.m.f. supplied the motor.
2. Combinations of motors (*e.g.*, series and parallel).
3. Insertion of resistance in motor circuits.

Changing the e.m.f. supplied the motor is difficult of accomplishment in ordinary direct-current equipments, since some form of rotating apparatus is necessary to produce the desired result. Although this method has been suggested in one type of control, it has never been introduced practically. For alternating-current motors, changes in potential may be easily accomplished by taking taps from a transformer or an auto-transformer to give the desired values.

A simple and efficient means of varying the e.m.f. applied at the motor terminals is available when an equipment consists of two or more motors, by placing them either in series or in parallel with one another. Two-motor equipments can thus be arranged to take full potential and half potential at their terminals; three-motor equipments (if such were used) could have full potential and one-third potential; and four-motor equipments full, one-half and one-quarter potential. This method of reducing the pressure is used in nearly all direct-current equipments. When this method of reducing potential is used, it is necessary that all the motors in

the combination have identical characteristics, since otherwise they will not divide the line e.m.f. equally when in series, or the current equally when in parallel. No troubles of this sort are to be anticipated from modern motors as received from the manufacturer, provided only machines of the same type and rating are used together. In case motors have been repaired by unskilled workmen, it may be necessary to test them in order to be sure that the performance has not been changed. If these precautions be taken, the motors will divide the pressure equally among themselves at all loads when in series (see Fig. 41). Since the current taken by motors in series is the same, the load imposed on them must in that case be equal. The only condition which can then cause trouble is that one motor may revolve faster than the other, due to slipping of the wheels. When this happens, the motor whose driving wheels are slipping will develop a greater counter e.m.f. than the other, which will then tend to run at a reduced speed, until it finally stops, the first motor revolving with but a small load due to the sliding friction of the wheel on the rail. To overcome this difficulty the motors must be stopped and the rail sanded.

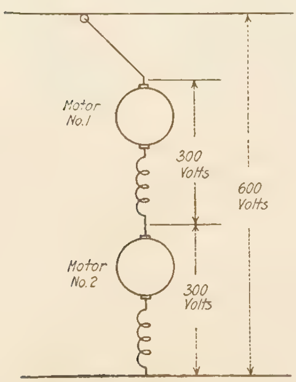


Fig. 41.—Division of e.m.f. with motors in series.

With direct-current motors, the insertion of series resistance has a similar effect to a forced reduction of potential. Since such an added resistance increases the *IR* drop, the amount of reduction in pressure at the motor terminals varies directly wtih the current. A resistance which will reduce the terminal potential of a motor to a low value with a heavy current will have but little effect on it at light loads (see Fig. 21). The effect of series resistance is quite different in the various types of direct-current motors. In the series motor it serves merely to reduce the pressure at the armature terminals, without affecting the field strength for a given armature current; but in the shunt motor, it reduces the field current as well. The result in this case is similar to that already noted for forced changes in motor potentials; and, if it is desired to control the shunt motor in this manner, the resistance should be placed in the arma-

ture circuit alone, the field being permanently connected to the line.

A reduction in the potential supplied an induction motor-affects it in much the same way as with the shunt motor. Since the armatures of several machines cannot be placed in series, as with direct-current shunt motors, this method of control has but little application.

Changes in Armature and Field Strength.—Since the torque of a motor depends on the product of field flux and armature current, a change in the flux will cause a proportional variation in the torque for a constant value of armature current. Likewise, since the speed depends directly on the counter e.m.f. and inversely on the field flux, a change in flux at any value of armature current will cause an inverse effect on the speed. In the shunt motor the field strength may be readily varied by inserting resistance in series with the field windings; but in the series motor it is less easy to make the change. There are four methods which may be employed to vary the field strength in series motors, as follows:

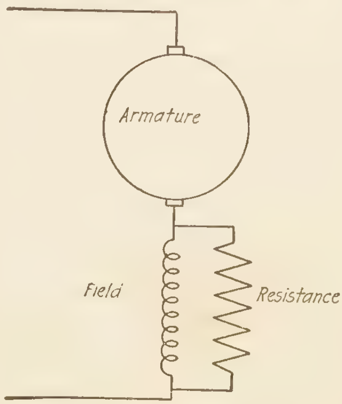


FIG. 42.—Field weakening by diverting resistor.

This method of field weakening has been abandoned on account of inductive troubles produced.

1. Placing resistance in *parallel* with the field winding.
2. Short-circuiting portions of the field winding.
3. Cutting out of circuit portions of the field winding.
4. Placing halves of the field coils in series and in parallel.

Of these methods, the first, shown diagrammatically in Fig. 42, was used in the early days of electric railways. It was soon abandoned on account of the severe sparking occasioned with the weakened field. In the motors of that period the problem of commutation was not understood so well as it is at the present time, and the margin of field strength was not great enough to permit this practice. With modern motors, equipped with interpoles, the commutation is so much better that a certain amount of field weakening is permissible without any trouble

from sparking. Further, in the designs arranged for this method of control, the flux with the full field in circuit is considerably greater than for the ordinary motor not arranged for field weakening.

The use of a resistance in parallel with the field is, however, open to several objections. It places a non-inductive path for the current in parallel with a highly inductive one. If the load is suddenly varied, the resulting change in current will at first be practically all made through the resistance, on account of the inductive effect of the field winding. The current will afterward gradually build up in the field coils; but sometimes not

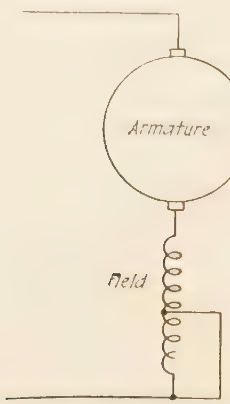


Fig. 43.—Field weakening by short-circuiting turns.

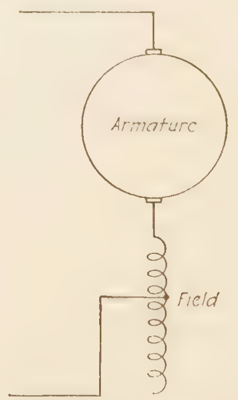


Fig. 44.—Field weakening by cutting out turns.

This method and that shown in Fig. 43 are in general use where field control motors are employed. The reduction in the number of turns is usually from 20 to 30 per cent.

until considerable damage has been done due to sparking or flashing at the commutator under the abnormal conditions.

The second method is to be preferred to the first. In this, as shown in Fig. 43, all the current must pass through the field winding, no matter what momentary variations in current strength there may be. This is a marked advantage over the use of parallel resistance.

The third method, illustrated in Fig. 44, is electrically the same as the second, and gives precisely the same results. The only difference is that the portion of the winding not in use is entirely cut out, instead of being merely short-circuited.

In the fourth method, Fig. 45, the turns which are removed from the circuit in the second and third methods, are connected in parallel with the other portion of the winding. This arrangement will only allow of two combinations, with full and half ampere turns. It has the advantage over the second and third methods of loading all parts of the field winding equally.

The efficiencies of the first three connections are identical, if the amount of field weakening is the same. Consider the field strength reduced to one-half its normal value by each method. In the first this will be accomplished by placing a resistor in parallel with the field whose resistance is equal to that of the field winding. The total resistance of the combination is one-half that of the field alone, and the ampere turns in the field coils one-half the normal value for the same armature current. With the second or third methods of connection, the resistance is reduced to one-half the normal value, since one-half of the winding is removed from the circuit. The efficiency of either connection is, therefore, the same as for the first. In the fourth connection it is greater, since, when the two halves of the field are connected in parallel, the resistance of the combination is but one-quarter the normal value. In any of the four methods of connection, the ampere turns on the field will be the same, if the parallel resistance is equal to that of the field, if one-half of the field turns are short-circuited or cut out of the circuit, or if the halves of the winding are connected in parallel instead of in series. The one to be used in any particular case depends on the size of the motor and the conditions of operation. For small machines, either the second or third method of connection may be used to advantage. For large locomotive motors, the additional complication of the winding and connections in the fourth method is warranted on account of the lower loss and the smaller heating.

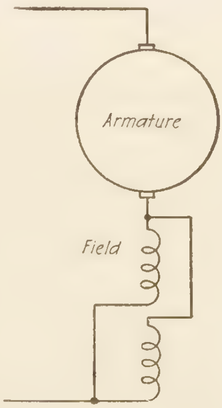


FIG. 45.—Field weakening by placing fields in parallel.

This method is usually applicable only to the larger locomotive motors.

Changes in Number of Poles, and in Frequency.—These methods of control are only applicable to induction motors. They will be considered in detail in connection with the control of motors of this type.

Practical Combinations of Control Methods.—In the practical control of railway motors, one or more of the methods outlined in the preceding paragraphs may be used to give the proper variation in characteristics desired. The simplest method is to control the potential; for alternating current this may be readily done with the aid of a transformer. For direct current, no simple, and at the same time efficient, method is available. For small equipments, or those which are infrequently started, the plain rheostatic method is the simplest and most rugged combination that can be used. The chief disadvantage lies in the waste of energy in the resistors. The method in most general use is a combination of the rheostatic control with changes in arrangement of the motors, placing them in series and in parallel. Since there are several methods of accomplishing the results sought, they will be taken up more in detail in the succeeding paragraphs.

Rheostatic Control.—The simplest way of controlling the performance of one or more series motors is by the rheostatic method. Resistance is placed in series with the motor or motors, the value being determined by the current desired through the motor at starting. Taps are taken from the resistors at certain points, so that the resistance may be varied from the maximum value to zero in a fixed number of steps. The proportioning of the resistance values is done in the same way as for series-parallel controllers, and may be determined as in the example under that heading. It must be remembered that since there is usually only one motor, the full line potential will be impressed on the motor circuit at the start, and the values of resistance must be determined accordingly.

A number of practical controllers have been designed using the rheostatic principle. All of the early ones were of this type, the series-parallel connection not being widely adopted at first. The best known modern controllers of this kind are the Type R, which are sold by the leading electrical manufacturers in this country. A number of sizes are built, the main difference being in the capacity of the motors which can be handled. A controller of this type consists essentially of a rotatable drum carrying a number of copper segments arranged to make the proper sequence of connections. A set of fingers, connected to the various external circuits, are brought to bear on the segments as the drum is revolved beneath them.

The development of a rheostatic controller, known as the type R-17, is shown in Fig. 46. This controller is suited for use with one 40 kw. motor. The operation may be readily traced from the diagram, the maximum resistance being connected in series on the first point and cut out in steps until the motor is working on the full line potential. With this type of controller, as with any rheostatic control, there is but one running point, that where the motor is connected directly to the line. On that point all the resistance is short-circuited, and the loss in the controller is simply that of any closed switch.

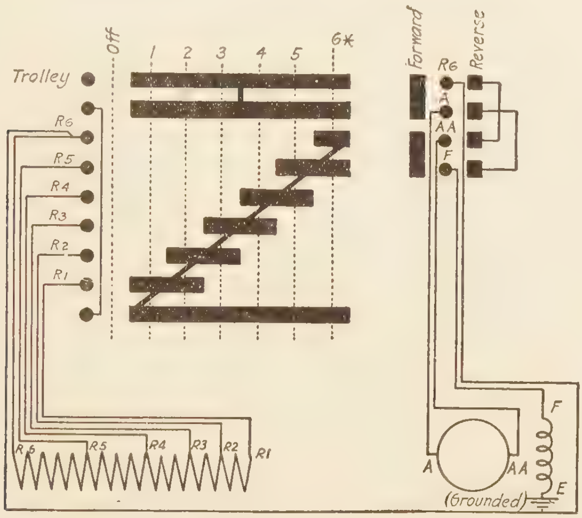


FIG. 46.—Development of type R controller.

This form of controller is used principally for the control of single motors for mining and industrial work. It is seldom employed for railway cars.

Rheostatic controllers are also made for operation with several motors, permanently connected in series or in parallel; and in some others of this type, provision is made for connecting motors in series or in parallel by means of a commutating switch located in the same case, and sometimes on the same shaft with the reversing drum.

Limitations of Rheostatic Control.—Controllers of the rheostatic type, while they are of the greatest simplicity, and are extremely rugged, are limited in their present application almost entirely to mining locomotives. Practically none are used on electric railways of any description, having been superseded entirely by series-parallel controllers. The reason for this is

found in their low efficiency of operation. During the period while resistance is connected in series with a motor or a set of motors, a portion of the electrical input is being consumed in the

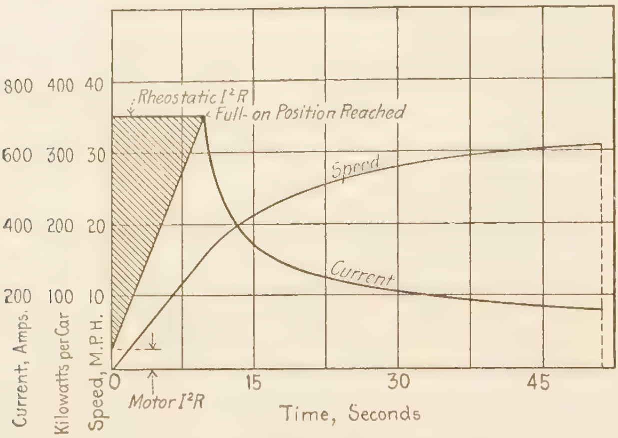


FIG. 47.—Energy loss with rheostatic control.

The shaded area represents the energy wasted in resistance. It is nearly one-half of the entire input while the controller is being turned to the full-on position.

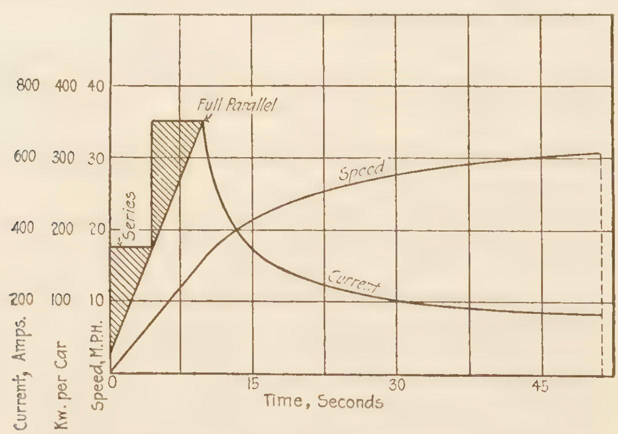


FIG. 48.—Energy loss with series-parallel control.

In this control the wasted energy is but one-half as great as in the rheostatic control. Approximately one-fourth the input shown in Fig. 47 has been saved.

resistors. The input to the motors is therefore less than the input to the train by the amount consumed in the wiring and in the resistors. For short runs this may amount to a very considerable part of the total input if rheostatic controllers are used.

In Fig. 47 is shown a curve between power input and time for a certain run, using four motors in parallel with rheostatic control. The shaded area is a measure of the energy used in the resistors. This shaded portion represents approximately one-half the total input during the period while the controller is being turned to the full-speed position.

The same motors may be connected in groups of two in parallel, and operated with a series-parallel control to give the same acceleration. In Fig. 48 is shown the curve of input for this form of control. The shaded area, representing the loss, is only one-

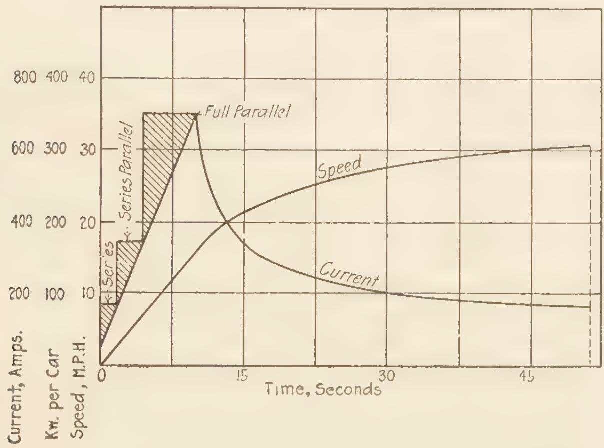


FIG. 49.—Energy loss with series, series-parallel control.

The energy saving over the series-parallel control is much less than that of the latter over the rheostatic. For this reason it has not a very wide application for light railway service.

half as large as in Fig. 47. This saving amounts to one-fourth of the total energy input during the time of operating the controller, and is a considerable portion of the entire input for the run.

Following the same line of argument, it may be seen that a controller can be arranged to put all four motors in series, re-connect them in series-parallel at the proper time, and finally place them in full parallel. The power curve for such a control is shown in Fig. 49. It may be noted that the saving in energy is about one-half of that lost in the series connection of the single series-parallel control, and one-eighth of the loss by the rheostatic method. It is only one-sixteenth of the input during the acceleration period, and a much smaller portion of the entire energy input for the run. While any saving of energy is a good

thing, the resulting complication of the controller is so great that it usually overbalances the gain. The saving incident to the series-parallel over the rheostatic control is so much larger that the complication is thereby justified.

Another advantage may be gained by the use of series-parallel control. With the rheostatic method, there is only one efficient operating point, that being the position with all resistance cut out of circuit. For reduced speeds it is necessary to waste a large amount of the input in the resistors. By the use of single series-parallel control, a second efficient operating speed becomes available when the motors are connected in series. The efficiency of the motors on half-potential is slightly less than under normal conditions, but it is quite high compared with the efficiency when half-speed is obtained by rheostatic control. Even without the saving in energy during acceleration, the complication of the control is justified to obtain the second operating point, which gives approximately half the full speed.

By the use of the series, series-parallel control, an additional operating speed of about one-fourth the normal may be obtained. This is not needed in ordinary car operation; but in the case of locomotives which must do a certain amount of switching and slow-speed yard work, the extra efficient speed will justify the added complication. It is only used on a few of the larger locomotives which are designed for normal high speeds. Generally speaking, all of the controllers for direct-current series motors are of the single series-parallel type, either with two-motor or four-motor equipments.

Series-Parallel Control.—Practically all direct-current railway motor equipments consist of two, or multiples of two, series motors, controlled by the series-parallel method. The basic principle of this control is, as has already been stated, to first put the two motors in series with resistance, next to cut it out of the circuit in a few steps, then to change the connections to parallel with a certain amount of resistance, and finally to cut it out again in steps. In some types of series-parallel control, the additional feature is included of reducing the field turns on the parallel connection after the external resistance is short-circuited.

The main differences in the arrangements of series-parallel controllers are occasioned by the methods of changing from the series to the parallel connection. It may be easily seen that the change from series to parallel can be made by one of two methods

—to open the motor circuits entirely while re-connecting, or to short-circuit one of the motors. Small platform or "hand" controllers are usually of the latter type, and are made in various sizes, as required by equipments of different capacity.

Type K Controllers.—The best known series-parallel controllers in America are the "Type K." This type (see Fig. 50, which represents the K–11 controller) consists of a drum carrying a number of copper segments, the connections to the circuits being made through corresponding stationary fingers which press against the segments as the drum is rotated beneath them. The general arrangement is quite similar to that of the Type R rheostatic controllers. The small drum at the right is for the purpose of reversing the direction of rotation of the motors, this being accomplished by interchanging either the field or the armature connections. To prevent the destruction of the segments and fingers by arcing when breaking the circuits, the well-known action of the magnetic field on an arc is employed in the so-called "magnetic blow-out." A coil carrying the main motor current is wound on an iron core fastened to the cast-iron back of the controller case, which thus becomes one pole of an electromagnet. The other pole is of such a shape that the flux produced must pass across the places where arcing will occur, and tend to break the arc before it has damaged the contacts. Since the front cover of the controller is of sheet iron, a certain amount of flux passes through it instead of across the contacts, reducing the efficiency of the magnetic blow-out by as much as one-half.

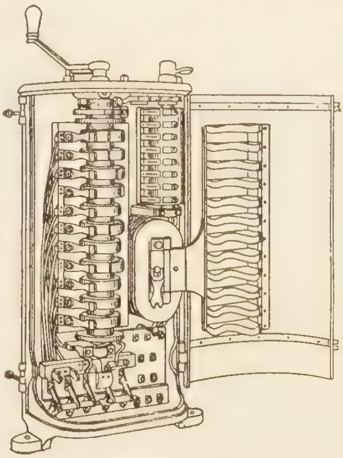


Fig. 50.—Type K-11 controller.
The type K controllers are very widely used in America for the control of fairly small motors by the series-parallel method. Practically all street cars use this form of controller.

The contacts on the reverse drum are not made sufficiently heavy to stand arcing, and they are not protected by a magnetic blow-out. It is hence necessary to prevent the reverse drum being thrown while current is passing through the contacts. This is accomplished by interlocking the two drums together

by a dog, which prevents motion of the reverse lever except when the main controller handle is in the "off" position. Since it is inadvisable for the motorman to leave his car in such condition that there is any possibility of irresponsible persons operating the controller, an interlock is arranged so that the reverse lever cannot be removed except when the drum is in the "off" position, *i.e.*, midway between the "forward" and "reverse" positions. When the reverse lever is removed, another interlock will prevent the rotation of the main drum; hence the

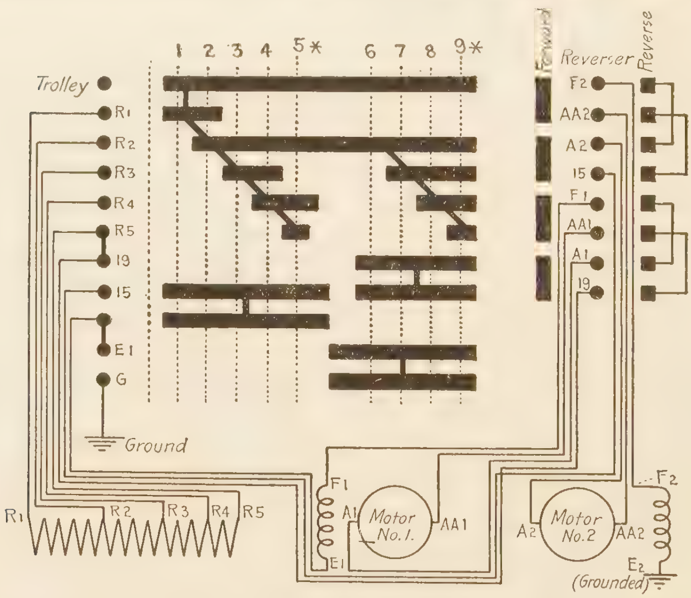


FIG. 51.—Development of Type K-10 controller.

The Type K controllers are made in a number of different models. The one shown is suitable for the control of two series motors. The difference is principally in the number of resistance steps, and in the number of motors which may be connected to the reverse drum.

reverse drum cannot be improperly operated under any conditions that may arise.

In case of emergencies it may be necessary to operate the car with only one motor or pair of motors. Switches are provided (near the base of the controller) to cut out of the circuit either one. When one of the motors is out of the circuit, there is no object in turning the controller drum beyond full series, since that position will place the motor on the line without resistance. The switches for cutting out the motors are provided with interlocks preventing

the drum from being turned beyond the last series notch when either switch is closed.

A development of the K–10 controller is shown in Fig. 51. From this diagram the sequence of connections may be clearly traced. The points which are suitable for continuous operation are designated as "running points." It is obvious that it would be unwise to operate continuously with external resistance in the circuit on account of the reduction in efficiency. Moreover, the resistors are not designed to carry the motor current for more than a few minutes without overheating.

When it is desired to use a controller of this type with an equipment of four motors, the main drum is exactly similar to that of a two-motor controller. The motors are permanently arranged in groups of two; and the only difference in the controller is the extension of the reverse drum to provide additional contacts for the field and armature circuits of the four motors. Generally, the two machines of a group are placed in parallel; but if the equipment consists of four 600-volt motors to be operated on a 1200-volt circuit, the pairs will be arranged in series. On some roads, where a portion of the line is at 1200 volts and another portion at 600 volts, the motor connections may be changed by an independent switch, which is interlocked with the controller to prevent improper operation.

Type L Controller.—The "Type L" controller, which was formerly much used for the heavier equipments, is similar in its general mechanical design to the Type K. The main difference is in the method of changing from the series to the parallel connection, which is accomplished by opening the motor circuits while making the change, as shown in Fig. 52. This type of controller has been practically superseded by various forms of so-called "multiple-unit" control.

A few years ago, considerable trouble was experienced on account of controllers being used for handling heavier currents than they were designed for. This sometimes resulted in the contacts being completely burned out, or at least rendered useless temporarily. This became so serious that the leading manufacturers have placed on the market an improvement in providing an automatic switch for closing and opening the main circuit so that the controller drum is relieved of this duty. This switch is operated electrically from the main controller, but is mechanically independent of it, usually being placed beneath the car.

Some of the ordinary types of platform controller have been modified by being provided with an auxiliary trip on the main drum, which prevents the contactor from closing until the operating handle has been turned to the first notch, after which the circuit operating the switch is closed. This prevents burning of the fingers on closing the main circuit. When the drum is turned backward to cut off the current, the operating circuit is opened before the drum has been returned to the off position, so that in this case the arc is also taken by the contactor. This system may be further developed by using the switch under the car as an auxiliary circuit breaker, whose tripping coil is in the trolley circuit, and whose jaws are in the operating circuit of the contactor.

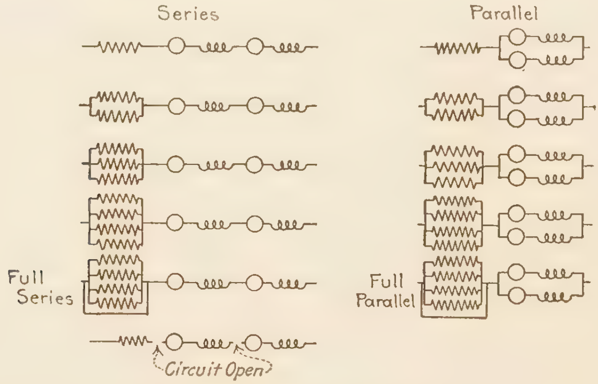


Fig. 52.—Circuits of Type L Controller.

This controller was formerly much used for large equipments, but has now been superseded by the various forms of multiple-unit control, as shown in Figs. 53 and 54.

It can be set to open at any desired value of current within its operating limits. When the current reaches this value, the tripping coil breaks the operating circuit, thus opening the main contacts.

Multiple-Unit Control.—When it is desired to operate a number of cars in a train, there are two general methods of procedure. The cars may be left without electrical equipment, and the power concentrated in a locomotive; or each car, or as many of them as required, may be equipped with electric motors and controllers. There are many arguments against the use of locomotives in this type of service, and in general the use of motor cars is preferred. The successful operation of a train of motor cars depends to a great extent on having the motors divide the work equally.

To do this the controllers must all be moved at the same rate. This cannot be done satisfactorily by having a motorman on each car, since it is practically out of the question to have them synchronize their movements. Further, this would increase the cost of platform labor to a prohibitive amount.

The ideal system is one in which all the motor cars are controlled by one motorman, who can be located at any convenient position on the train, as at the front of the leading car, whether that be a motor car or a trailer. In addition, it is desirable to be able to change the number of cars in a train at will, depending on the amount of traffic. All these advantages may be obtained with any one of the forms of multiple-unit control now in use on the large electric roads in all parts of the country.

Sprague System.—The earliest method of control of the multiple-unit type was the Sprague system, invented by Lieut. Frank J. Sprague, and first used on the South Side Elevated Railway in Chicago. In this system the main or motor controller was a drum similar to that of the Type K platform controller, but differing from it in being operated by a "pilot motor." This latter was under the control of the motorman, who could cause its armature to rotate, thus revolving the main control cylinder and making the proper connections for the acceleration of the car motors. A number of novel devices were incorporated in this type of control. In order to start the car, all that was necessary was for the motorman to start the pilot motor in operation, which would begin the revolution of the main controller drum. The rate of movement of this drum was limited by the propulsion current. A relay was interposed in the main control circuit, and so arranged that if the live current exceeded a predetermined amount, the circuit of the pilot motor would be broken, stopping the movement of the main drum until the live current fell below the limiting value. Then the pilot motor would again be connected to its circuit and the cylinder be revolved further. This action would continue until the propulsion motors were in the full parallel connection. A number of other relays were introduced to make the operation more certain, and to prevent abuse of the equipment. Magnetic blow-outs similar to those used on the platform controllers were employed. In general, its operation was quite satisfactory for fairly small cars, taking not over about 150 kw. total capacity.

Type M Control.—When the original Sprague controller was used for heavy equipments it was found inadequate; so when the Sprague patents were purchased by the General Electric Company the manufacture of the original Sprague control was abandoned, the "Type M" control being substituted for it. This latter, shown diagrammatically in Fig. 53, utilizes the principle mentioned in connection with the heavy Type K controllers of breaking the circuit in specially designed contactors. A set of magnetically operated switches is substituted for the drum.

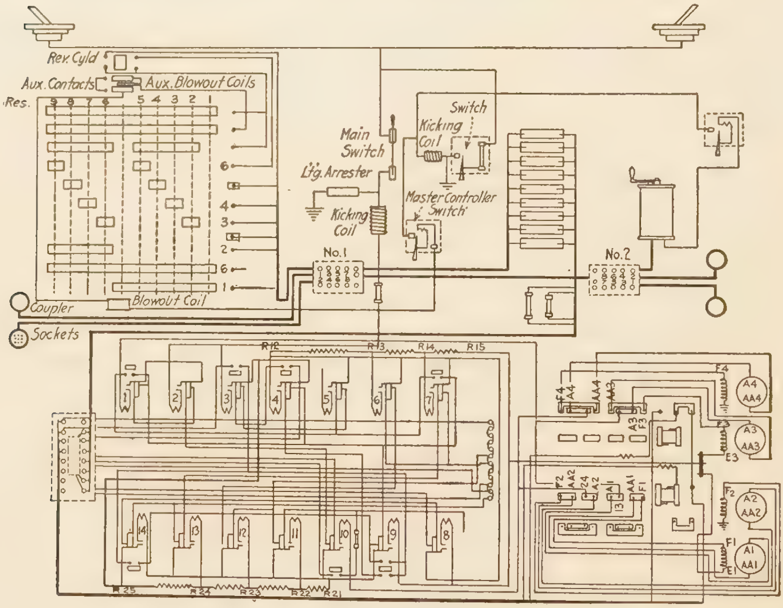


FIG. 53.—Circuits of type M controller.

This type of controller is very widely used on elevated and interurban cars. Motors of practically any capacity may be handled.

These are actuated by a small current from the trolley, and their movement is governed by the motorman through a "master controller," whose function is to admit current to the proper switches and secure the correct sequence of closing and opening them to obtain the desired combinations. The location of the master controller may thus be practically independent of the main controller, the only connection being through the small wires for supplying current to the magnets for operating the main switches of the control. Two types of operation are standard: that providing manual control of the switches, and that in which

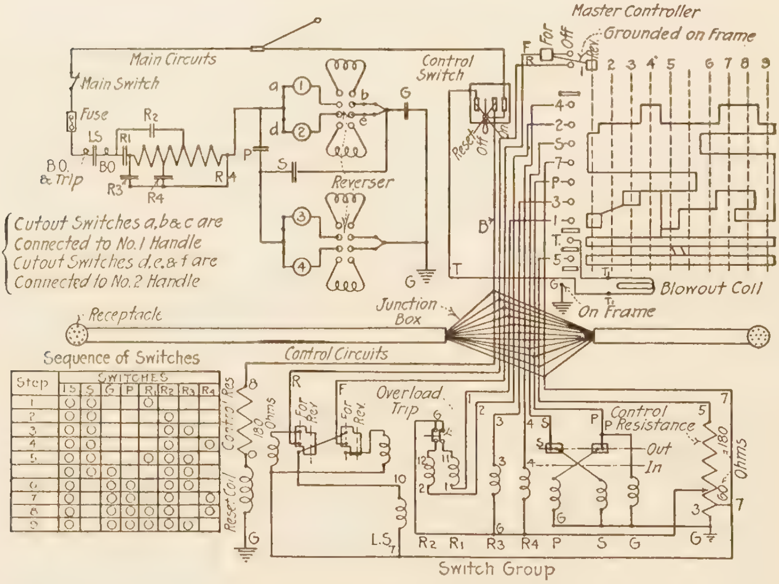
the movement of the switches is automatically governed by the motor current, as in the original Sprague system.

The essential element of the system, the "unit switch" or "contactor," is a switch actuated by an electromagnet. Each of these units may be considered as replacing a finger and its corresponding segment in the hand-operated controllers, and consists of a pair of contacts, one of which is fixed, and the other moved by the action of the solenoid. The pair of contacts operate in an arc chute of moulded insulation with an individual magnetic blow-out. To insure the proper sequence of closing and opening the switches, interlocks are provided for making the necessary connections. All of the contactors are placed in a covered metal box mounted on an insulated support beneath the car, or in the cab of the locomotive. Since each contactor is independent of the others, the capacity of the switch may be made as large as required for the particular case. The size of motors which can be handled is not limited, as with the drum type of controller. In case the desired capacity is too great for a single switch, two or more may be placed in parallel to subdivide the current.

The automatic control provides for the acceleration of the train at a predetermined value of motor current, although it does not prevent manual operation of the controller at a lower rate if desired. The arrangement is quite similar to that described for the original Sprague control. The operation of the contactors is governed by a limit switch in the motor circuit, so that the motor current while accelerating is confined within a definite range. This is accomplished by having interlocking contacts on certain of the switches, the movement of each connecting the magnet coil of the next succeeding contactor to the control circuit. Under all conditions the contactors are energized in a definite order, as described in the general paragraph on the series-parallel controller. The progression of switches can be arrested at any point by the master controller, and is also governed by the limit switch, so that the rate of movement is never beyond that which will keep the motor current within the prescribed range.

Unit Switch Control.—The system used by the Westinghouse Company is quite similar to that just described, differing mainly in the means used to operate the individual "unit switches" or contactors. While in the Type M system the switches are operated electrically by means of current taken from the line, in the Westinghouse control they are actuated by means of com-

pressed air supplied from the air-brake reservoirs. The admission of air to the operating cylinders is controlled by electrically operated needle valves. The current for them may be obtained either from a low-potential storage battery or from the line. The main claims in favor of this type of control are that a more positive action of the switches may be obtained on account of the greater pressures possible between the contact fingers. The general features of operation are quite similar to those of the Type M control; in fact, both equipments may be arranged to be oper-



Step	SWITCHES							
	LS	S	G	P	R1	R2	R3	R4
1	O	O			O			
2	O	O				O		
3	O	O				O	O	
4	O	O				O		O
5	O	O			O	O	O	
	O	O	O			O	O	
6	O		O	O		O	O	
7	O		O	O		O		O
8	O		O	O	O	O		O
9	O		O	O	O	O	O	

FIG. 54.—Circuits of type HL control.

In this type of controller the magnetic switches of the Type M controller are replaced with electrically controlled, pneumatically-operated switches. Controllers of this general type are made for a wide range of equipment.

ated together on one train from one master controller. Fig. 54 gives a diagram showing the connections of this control.

Bridge Connection.—In some of the types of multiple-unit control, as well as in some of the later Type K controllers of large size, the change from series to parallel is made without either short-circuiting or open-circuiting the motors. This is accomplished by the "bridge" connection. It consists in putting a resistance in parallel with the motors, and through it making the change. This is shown in Fig. 55. The principle of the bridge

connection is to have the resistance placed in parallel with the motors such that the current flowing through it is practically the same as the motor current. Then when the connections are changed to parallel, there will be no disturbance in the total current taken by either motor or by the line. The success of this arrangement depends on having the motor current at the instant of making the change the same as that through the resistance. For this reason the bridge connection is best suited to automatic control, where the current is limited by electrical relations only.

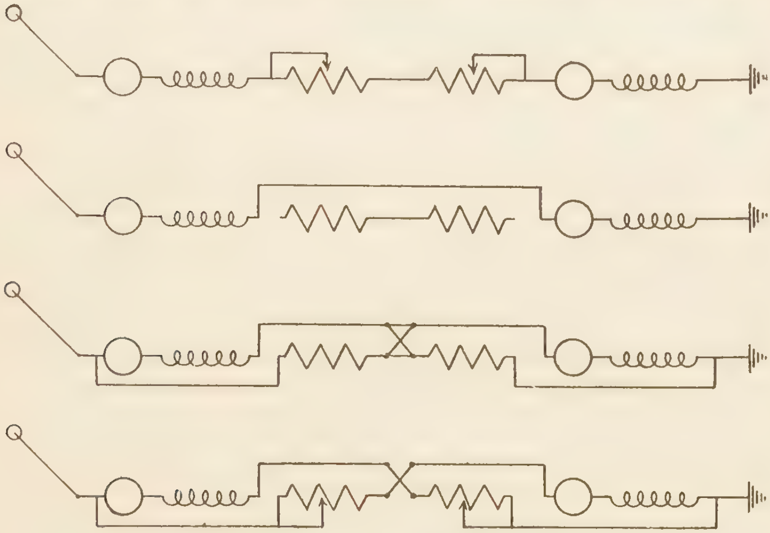


Fig. 55.—Bridge method of transition.

This method makes the change from series to parallel without breaking the circuit through either motor, and without causing any great disturbance on the line. It is widely used in connection with controllers of the multiple-unit type.

Pneumatically-Operated Drum Control.—The drum controller is at present the most compact and the most flexible device for producing a number of different combinations in electric circuits, and it is still the most suitable method of control for small equipments. With remote operation of the drum, and protection against arcing, it makes a satisfactory apparatus for multiple-unit control. A type of controller has been developed, primarily for single-car service on the New York City railways, but which is applicable for multiple-unit operation of any cars which are not too heavy. Mechanically, it consists of an ordinary drum controller, which is actuated by a pair of compressed-air cylinders

arranged to turn the main shaft through a rack and pinion. The reverse drum is also moved by air cylinders. Admission and release of air are governed by magnetically-operated needle valves, as in the unit switch control. A current limit relay is introduced in the control circuit to keep the motor current within a prescribed range. This device operates in the same manner as the limit switches already described with multiple-unit control.[1]

Jones Type Control.—A novel type of series-parallel control, suitable for use with four-motor equipments, has been brought out by Messrs. P. N. Jones and J. W. Welsh of the Pittsburgh Railways Co. It operates with a permanent series connection between all of the motors, and employs a minimum of resistance for securing the desired steps. At least three of the motors are in circuit at all times.

The connections on the different steps are shown in Fig. 56. The controller has seven points, of which three, numbered 2, 4 and 7, are operating positions. The current in some of the motors is reversed in making the changes; but since both armature and field are reversed together, the direction of motion is not changed. The first position places all the motors in series with a suitable resistance, which is cut out on the second point. One motor is completely short-circuited on the third notch, after which it is connected to the line through resistance. On the next transition point a second motor is reversed, thus placing it in series with the other and the resistance. On the fourth notch the resistance is cut out, leaving the motors in the series-parallel connection. The next transition point is similar to the other transition connections, except that but three motors are in circuit. The fifth and sixth positions are really transition steps; and the motors are placed in full parallel on the seventh notch. This type of control has been employed with success on the cars of the Pittsburgh Railways, which are equipped with motors having small diameter armatures on account of the small-sized wheel. It is stated that the control will work equally well with standard motors. For further details of the apparatus and arrangements of the circuits reference may be made to U. S. Patent No. 1,109,338, issued September 1, 1914.

Proportioning of Resistances.—In any of the methods so far devised for the control of direct-current series motors, it is not

[1] For a detailed description of this type of control see *Electric Journal*, October, 1913.

sufficient to reduce the potential at the motor terminals by the use of different combinations of motors. To prevent an excessive flow of current, and to keep the torque within rather narrow limits, it is necessary to introduce a certain amount of resistance into the circuit in series with the motors. The amount of this resistance should be just enough to reduce the starting current

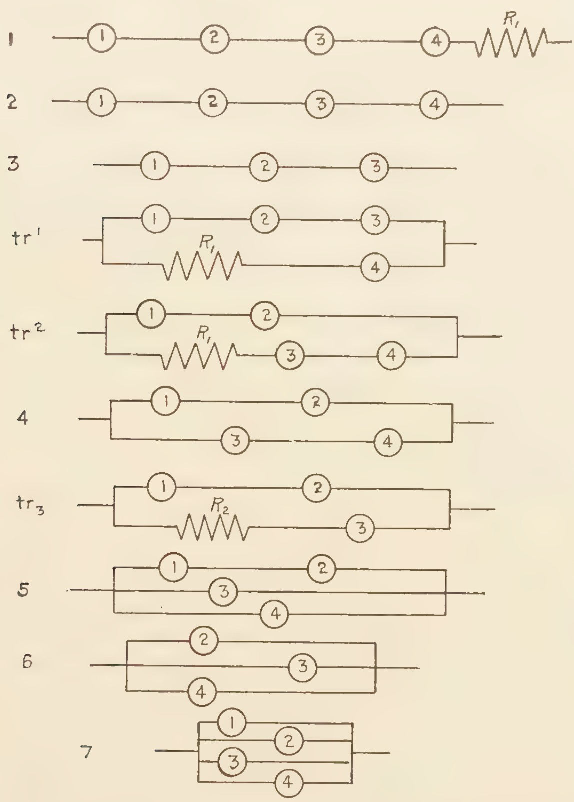


FIG. 56.—Jones type control.

In this control combination of the motors are used instead of the usual resistance, reducing the energy loss while starting, and giving a greater number of running points.

and the torque to the desired limiting values allowable for the equipment. As the motors gain speed, the amount of resistance must be lessened, until it is all removed from the circuit. This may constitute the entire control, or it may be done in conjunction with changes in the arrangement of the motors, such as connections in series and in parallel.

At standstill, the current flowing through the motors is limited only by the resistance of the windings of the two motors connected in series, unless sufficient external resistance be inserted to cut the current down to some specified value.

As an example, take the 50 kw. railway motor, curves for which are shown in Fig. 19. It is desired to accelerate a certain car by using a pair of such motors with series-parallel control at such a rate that the current will vary between the limits of 200 amp. and 150 amp. while resistance is included in the circuit. The actual determination of the limiting values of current depends on the weight of the car, the desired acceleration, and the allowable load on the motors. The difference between the maximum and minimum values of current is determined by the number of steps on the controller, which in its turn depends on the permissible variation from the mean acceleration.

At standstill the current will have the maximum value, and the necessary resistance to be used will be found by Ohm's law:

$$I' = \frac{E}{R_1 + 2r} \tag{1}$$

where I' is the maximum current, E is the line e.m.f., R_1 the external resistance, and r the motor resistance. In the example cited, $r = 0.232$ ohm, hence

$$200 = \frac{500}{R_1 + 2 \times 0.232}$$

whence $R_1 = 2.036$ ohms. This represents the total resistance which must be added to the motor circuit to keep the first rush of current down to the desired limit.

With current passing through the motors, a torque will be developed, which will cause the car to accelerate. As the car gains speed, the motors develop a counter e.m.f., the production of which causes a decrease in the motor current, and hence in the tractive effort and the acceleration. In order to keep the tractive effort within the limits desired, the resistance should be reduced when the current has fallen to the minimum value decided on.

When the current has fallen to some value I'', the counter e.m.f. developed by the two motors in series, $2E_c$, will be

$$2E_c = E - I''(R_1 + 2\,r) \tag{2}$$

It is then necessary to determine the new value of external resistance R_2 which will cause the current through the motors to increase to the maximum value I'. The reduction in resistance will be made instantaneously so that there will be no opportunity for the speed to change during the operation of the controller from one notch to the next. If the field flux remained constant with variations in armature current, as in a shunt motor, the counter e.m.f. would be the same after the resistance had been reduced, except for the small change in IR drop in the motor windings. But with the series motor, an increase in armature current carries with it a corresponding increase in field flux, so that the counter e.m.f. will also be greater. In order to find the amount of this rise in counter e.m.f., the saturation curve of the motor may be used, and the two values of flux corresponding to the currents I' and I'' determined from it. The ratio of increase can also be found from the curve of torque per ampere, Fig. 22.

In obtaining the rise of counter e.m.f. when the resistance is reduced so that the current increases from I'' amp. to I' amp., it is only necessary to determine the ratio of tractive effort per ampere for the two values of current. That is,

$$\frac{E_{c2}}{E_{c1}} = \frac{\dfrac{D'}{I'}}{\dfrac{D''}{I''}} \tag{3}$$

where E_{c2} and E_{c1} are the counter e.m.f.'s at currents I' and I'' respectively, and D' and D'' the corresponding tractive efforts. The value of E_{c1} having been found already by equation (2), that of E_{c2} can be determined from equation (3). The new amount of resistance will have to be such as to give the counter e.m.f. E_{c2} when a current I' flows through the circuit, which will satisfy the equation

$$I' = \frac{E - 2E_{c2}}{R_2 + 2r} \tag{4}$$

This equation is similar in form to equation (1), but takes account of any value of counter e.m.f. which may exist at the moment.

Applying these equations to the example cited, we have, from equation (2),

$$2E_{c1} = 500 - 150\ (2.036 + 2 \times 0.232) = 125 \text{ volts}$$

This is the counter e.m.f. existing the instant before the resistance is reduced. The instant following the reduction, this becomes

$$2E_{c2} = 125 \times \frac{13.43}{12.40} = 135 \text{ volts}$$

The necessary value of resistance is determined from the relation

$$200 = \frac{500 - 135}{R_2 + 2 \times 0.232}$$

from which R_2 is found to be 1.361 ohms.

The same reduction in torque as the speed of the motor increases will be noted, and, when the current has fallen to 150 amp. the counter e.m.f. may be calculated by equation (2) as before. A new value of resistance may then be found by the use of equations (3) and (4). This process will be continued until all the resistance is cut out, and the motors are connected in series directly across the line.

To obtain further acceleration, it is necessary to reconnect the motors in parallel. The counter e.m.f. per motor will be the same; but when the connections are changed to parallel the two e.m.f.'s will not add. Equation (2) will have to be rewritten as follows:

$$E_{c1} = E - 2I''\left(R + \frac{r}{2}\right) \qquad (5)$$

Having obtained the new value for E_{c1}, that of E_{c2} may be found by equation (3). By this method the magnitude of all the parallel resistances may be determined.

Table I shows these values as computed for the problem outlined. In the columns for counter e.m.f., the upper values are for each motor (E_c), and the lower for the two motors when they are in series. In the columns for resistance, the upper values are per motor, and the lower for two motors in parallel.

It may be seen that on points 5 and 9, on which all resistance has been cut out, the current will not rise to quite 200 amp. This is unavoidable with the assumptions made.

Graphical Method of Calculating Resistances.—This method of calculation lends itself very readily to a graphical solution. Referring to Fig. 57 a diagram has been plotted between motor amperes and motor volts. If the line e.m.f. is 500, then when the two motors are in series, each will be taking 250 volts, less what is consumed in the resistance. The lines *SE* and *PJ* have been

TABLE I

Point of Controller	Speed		Counter e.m.f.		*IR* Drop		Resistance		
	200 amp.	150 amp.	200 amp.	150 amp.	200 amp.	150 amp.	Total	Motor	External
1	0.0	2.35	0.0	62.5					
				125.0	500.0	375.0	2.5	0.464	2.036
2	2.35	4.26	67.5	113.0					
			135.0	226.0	365.0	274.0	1.825	0.464	1.361
3	4.26	5.82	122.2	154.5					
			244.4	309.0	255.6	191.0	1.278	0.464	0.814
4	5.82	7.06	167.0	188.5					
			334.0	377.0	166.0	123.0	0.830	0.464	0.366
5	7.06[1]	8.09	203.6[1]	215.2					
			407.2[1]	430.4	92.8	69.6	0.464	0.464	0.0
6	8.09	11.24	232.0	299.0	268.0	201.0	1.340	0.232	1.108
							0.670	0.116	0.554
7	11.24	13.8	322.5	366.7	177.5	133.3	0.887	0.232	0.655
							0.443	0.116	0.327
8	13.8	15.8	395.0	421.0	105.0	79.0	0.525	0.232	0.293
							0.262	0.116	0.146
9	15.8[1]	......	453.6[1]	......	46.4	......	0.232	0.232	0.0

drawn at an angle such that the ordinate, as $S'E'$ or $P'J'$ represents the IR drop in one motor at any current I. The line SA has been drawn to represent the IR drop per motor for any value of current, when the resistance is so chosen as to bring the motor to a standstill at 200 amp. When the current has fallen to 150 amp., the total IR drop is represented by the ordinate $S'A'$, and the drop in external resistance by $E'A'$. If the resistance is then reduced so as to bring the current to 200 amp., the counter e.m.f. will be increased by the ratio given in equation (5). The curve $TYWT'$ between tractive effort per ampere and current has been plotted to the same base, although, if the current limits are to be those decided on, the points Y and W are all that need to be located. The straight line WYX is then drawn through Y and W, intersecting the current axis prolonged at X. It will be seen at once, from similar triangles, that any line drawn through X will produce intersections on the lines UP' and AP'' that are proportional. That is,

$$\frac{UA'}{AB} = \frac{UY}{AW}$$

[1] At 196 amperes.

and so on, for any possible line drawn through X. If then the line $XA'B$ is drawn through X and A' intersecting AP'' at B, the ordinate AB will represent the counter e.m.f. developed when the current has been increased from 150 to 200 amp. without changing the speed. The ordinate $S''B$ gives the total IR drop and EB that external to the motor; this latter, divided by the current, determines the new value of resistance. The IR drop will then decrease along the line BB' as the current falls off, until,

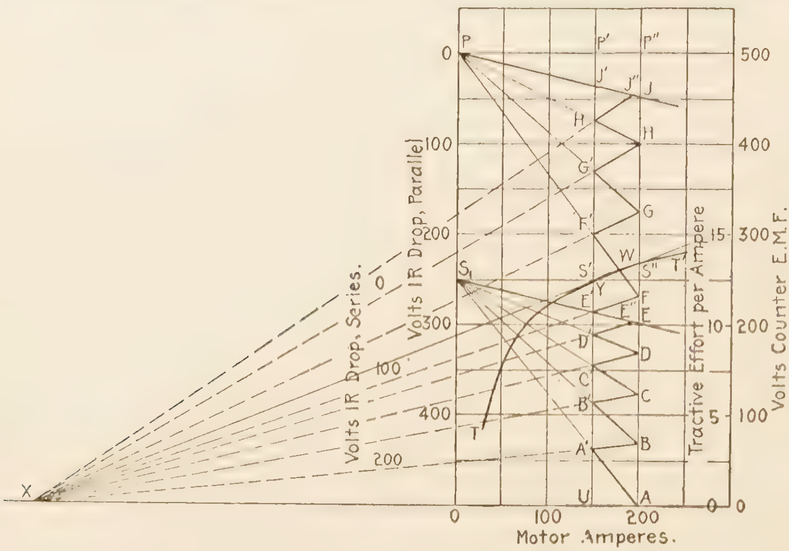


FIG. 57.—Volt-ampere diagram for determining resistance.

at point B', the current must be increased again. The same construction is repeated until the two motors are in series without resistance. The current which will be obtained when the last point of resistance is cut out may be readily determined, since the IR drop in the motor alone is plotted as SE. When the last line radiating from X is drawn it will intersect this line at some point as E''. The abscissa determines the current.

In changing to parallel, it is only necessary to move the axis of reference for IR drop to the proper point, in this case the ordinate for 500 volts, and continue the construction from that place. The remainder of the diagram is exactly the same as before.

As explained, the diagram is theoretically correct, and a comparison of the values found graphically for resistances with those calculated in Table I shows how closely they agree. Further,

the diagram may be used for any value of line potential without other change than shifting the origin for the *IR* drop. For different current limits it is necessary to take other points on the tractive effort per ampere curve, thus getting a new location for *X*. The shape of the curve, as drawn on the diagram, shows that a small variation may be made without relocating this point, and the error will not be great.

In general, as the resistors are used both for the series and the parallel connections, a certain amount of adjustment must be made of the values determined for definite current limits. The method of doing this may be seen at once from the construction. It is only necessary to continue the *IR* lines either above or below the limits set, and the proper values can be found directly.

If a controller is to be used with four motors, the changes in the method to allow for sets of two motors permanently connected in series or in parallel may easily be determined.

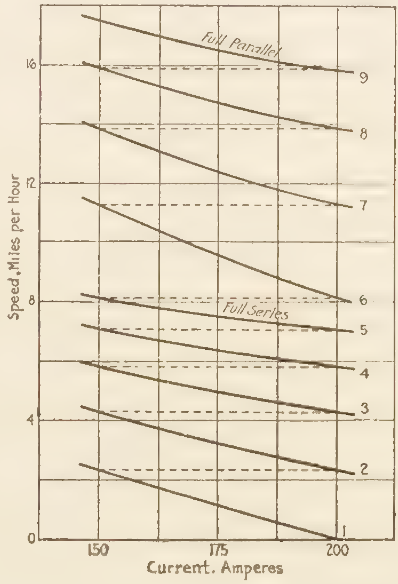


Fig. 58.—Speed curves for resistance points.

These curves, with the exception of the "Full Series" and the "Full Parallel" positions, are similar to that in Fig. 21, and may be calculated in the same manner.

Time for Operating Controller.—In Fig. 58 is given a diagram between motor speed and motor current for each of the points on the control, as computed in the preceding problem. From methods already outlined, the time when the controller handle should be moved from one point to the next may be obtained, if the car weight be known. For a given equipment, the time for operation of the controller has been found, and the relations between current and time are given in Fig. 59. It is noticeable that the length of time of operation on each point of the control is different, the time on the parallel points being considerably greater.

With a controller arranged for automatic acceleration, the resistance will be reduced at the proper time, and no attention need be given this phase of its action. With hand controllers the tendency is for the motorman to rotate the operating handle at a uniform rate. Should he do this, the resistances having been calculated for definite current limits, as outlined in the preceding

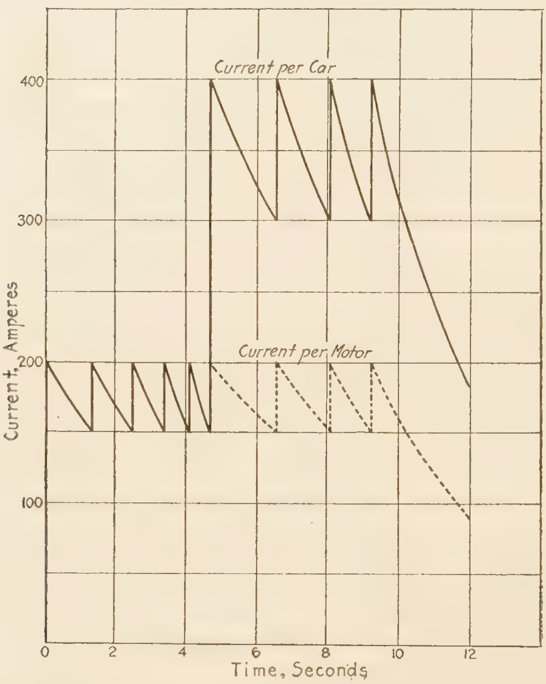


FIG. 59.—Current–time curve for starting a car.

This is the form of curve obtained when the resistances and the time of moving the controller handle have been correctly determined. Note that the time on the various points is not uniform.

paragraphs, the results will be quite different. Fig. 60 gives the values of current obtained when the controller, with resistances as determined previously, is rotated *at a uniform rate* such that all the resistance will be removed from the circuit at the same time as in the proper operation. The conclusion is obvious. Either the controller should be notched up at the proper rate, or the resistance should be re-calculated for a uniform length of time on each point.

Resistors for Railway Service.—In connection with the types of control already considered, it is essential that proper resistors be employed. The amount of energy to be dissipated is comparatively large, and the current-carrying capacity must be considerable. Further, the materials of which the resistors are made should be such that continual service, calling for repeated heating and cooling, will not cause injury to them.

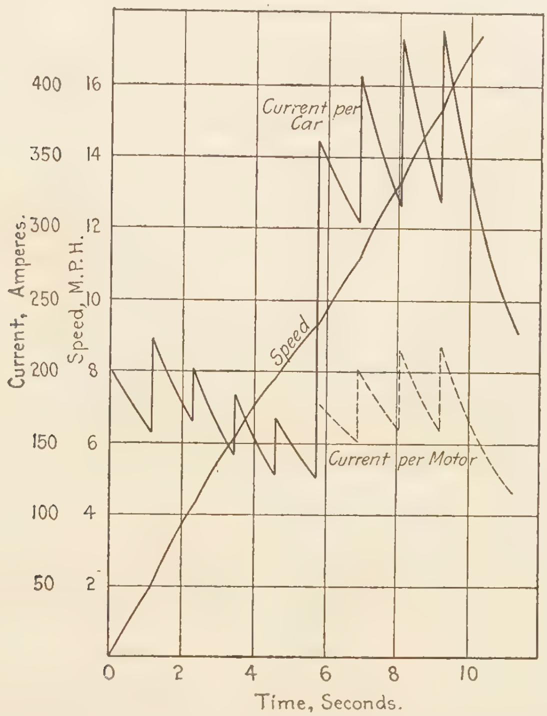


FIG. 60.—Starting current with improper operation of controller. The time increments on the successive points are uniform. Note that while the average value of the current is practically the same as in Fig. 59, it varies over a wider and non-uniform range; and the speed–time curve is not smooth.

In early equipments the resistors were chosen merely to give the proper resistance, without regard to their other qualities. A favorite type consisted of strips of German silver, interlaid with strips of mica, and rolled up into spirals. These were expensive, and heavy overloads would tend to burn them out. An improvement was introduced by ventilating the coils; but this did not make them very successful. They have been entirely superseded

for regular service by resistors of the cast grid type. The grids are made of cast iron, or of iron alloys, and are assembled in light frames in units of the proper capacity, as shown in Fig. 61. The grids are entirely open to the air, and if placed under the car or locomotive in such positions as will allow currents of air to reach them, they are entirely satisfactory. They are cheap and reliable, and, although the temperature coefficient is not negligible, it makes little difference, for it can be determined and allowed for.

A recent variation of the grid resistors is in making them of steel bar, bent to the proper shape and afterward case-hardened, instead of cast iron. This removes the greatest objection to the cast grid—brittleness—while not changing the other properties to any extent.

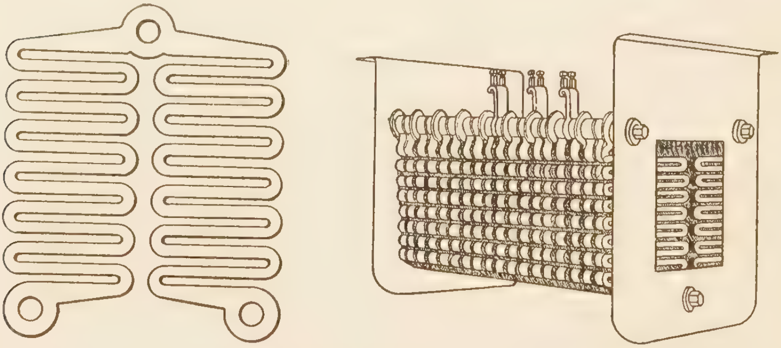


Fig. 61.—Assembled frame of grid resistors, and separate unit.
The resistors used with railway motor control are of this or similar types. They are made of cast iron in the form of grids, and assembled in frames, as shown.

A type which has found some favor, especially in connection with polyphase induction motor control, is the liquid or electrolytic resistor. A tank of the proper size and shape is provided with two metal electrodes and is filled with brine or other electrolyte. One of the electrodes is movable, so that the distance between them, and hence the resistance, may be changed by fine gradations. The acceleration does not have abrupt variations, such as must necessarily be occasioned when a limited number of fixed resistances are used. The water resistor is cheap, and is capable of getting rid of a large amount of heat, since the temperature of the electrolyte cannot increase beyond the boiling point, the generation of heat at that point causing ebullition of the electrolyte, releasing energy in the vapor.

Control of Single-Phase Motors.—Single-phase series motors can be controlled by the ordinary series-parallel method just described. Owing to the fact that the main justification for the single-phase motor is in the high trolley potentials which may be employed, it is necessary to use a stationary transformer on the car or locomotive to reduce the pressure to a value suitable for operation of the motors. This makes it possible to get an efficient

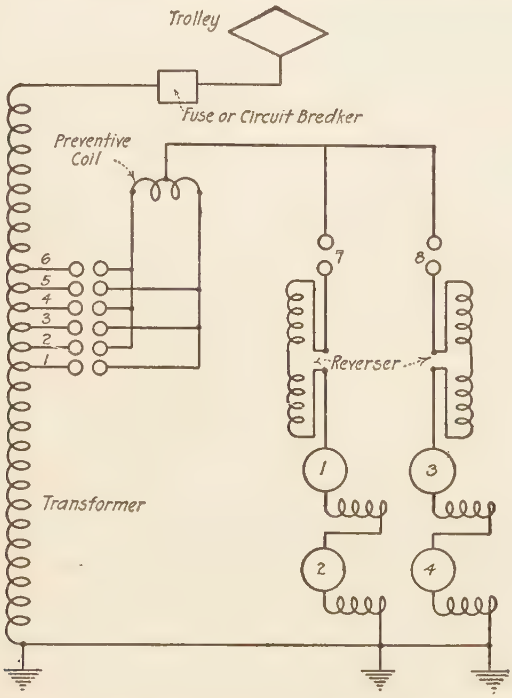


FIG. 62.—Transformer control for single-phase motors.

The motor performance is varied by connecting the machines to the different taps, 1, 2, 3, etc. in turn.

method of potential variation simply by bringing out from the secondary of the transformer a number of taps which may be connected in turn to the motors. A controller of this type is shown diagrammatically in Fig. 62.

Owing to the high efficiency of the transformer, each step on the controller may be used as an operating point, there being no loss due to the use of resistance, as with direct-current control. The motors are ordinarily placed permanently in parallel

or in series-parallel, and the entire variation in potential is obtained by changing the transformer taps to which the motors are connected.

In order to obviate breaking the circuit in shifting from one tap to the next, connection is made through a "preventive coil," which is a coil of wire on a magnetic core, designed to have approximately the same e.m.f. as the portion of the transformer winding it short-circuits. The lower terminal of the coil may then be disconnected and reconnected to the next higher tap without causing any disturbance in the system. The method is shown in detail in Fig. 63. For the heavier equipments a double

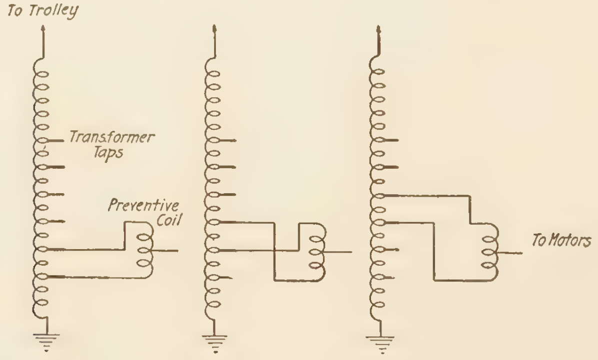


FIG. 63.—Use of the preventive coil.

By the use of the preventive coil the motors may be connected to the various taps on the transformer without breaking the circuit, and without any wide variation in tractive effort

set of preventive coils is used, making the operation still more smooth.

An induction regulator can be employed for varying the potential on the motors of a single-phase equipment, as shown in Fig. 64. This allows an absolutely uniform acceleration. Its use was proposed when the single-phase system was first projected; but experience has proved that the acceleration obtained with taps from the main transformer is smoother than in series-parallel control of direct-current motors with the same number of steps, and the use of the regulator has been unnecessary. In some of the larger European single-phase locomotives it has been employed with considerable satisfaction.

Combination Systems for Single Phase and Direct Current.—Since the single-phase series motor, when conductively compensated, is also an excellent direct-current motor, it may be oper-

ated equally well on a single-phase alternating-current circuit or on a direct-current circuit, provided the line pressure be correct. A number of the heavier single-phase equipments are arranged for both methods of operation. All that is necessary is to have proper controllers for each kind of current, and switches for changing circuits as the train passes from one source of supply to the other, as shown in Fig. 65. It is essential to guard against the possibility of wrong connections on the car, for an accidental

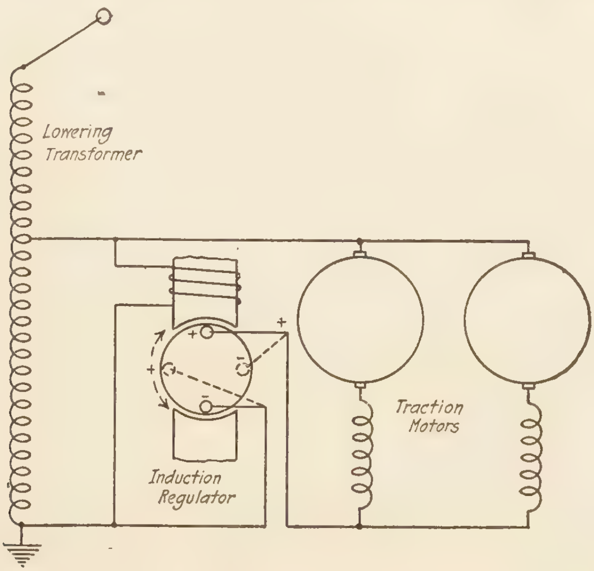


FIG. 64.—Induction regulator control for single-phase motors.
The transformer taps are replaced by an induction regulator, by means of which the motor potential may be varied by infinitesimal steps.

contact of the high-tension alternating circuit with the series-parallel controller would be disastrous. To prevent this, the main switch of the car equipment is provided with a retaining coil so arranged that it will open when the circuit is interrupted. Where the alternating- and the direct-current sections adjoin, a dead space is left between the two for a distance not exceeding a car length. A car may then pass from one section to the other at full speed, in which case the main switch opens on the insulated space through lack of power to operate the retaining coil, resetting automatically for the other form of power after passing the breaker.

Control of Three-Phase Motors.—Three-phase motors require entirely different forms of control from those previously described.

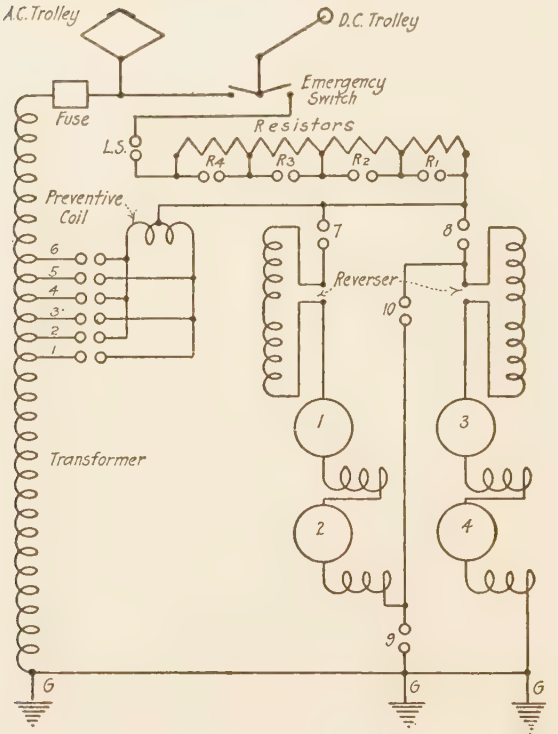


FIG. 65.—Combined single-phase and direct-current control.

A combination of the transformer control for the single-phase circuit with rheostatic for the direct current. On account of the complication, it is not used so much now as formerly.

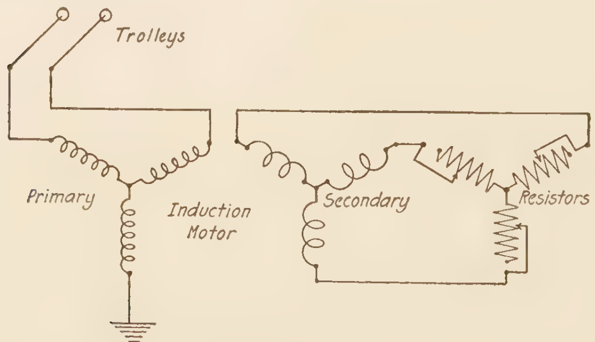


FIG. 66.—Three-phase motor control.

The leads from the secondary winding are brought out to collector rings, and short circuited through a set of variable resistors.

It has already been shown that reductions in the primary potential are inadvisable, since the torque of an induction motor varies approximately as the square of the applied pressure. The motor speed may be decreased without diminution of torque by placing resistance in the secondary circuits, as shown in Fig. 66. The effect of such resistance is approximately the same as when used in the armature circuit of the direct-current shunt motor, the torque for a given value of current being obtained at a lower speed when resistance is introduced. This method is open to the same objections as the rheostatic control for direct-current motors, in that the loss is great at reduced speeds. The efficiency of an induction motor is always slightly less than the speed in terms of synchronism. A reduction of the speed to one-half normal therefore decreases the efficiency to something less than 50 per cent. For classes of service where one operating speed is sufficient, and where stops are infrequent, rheostatic control is applicable; for other cases one or another of the methods described below may be used.

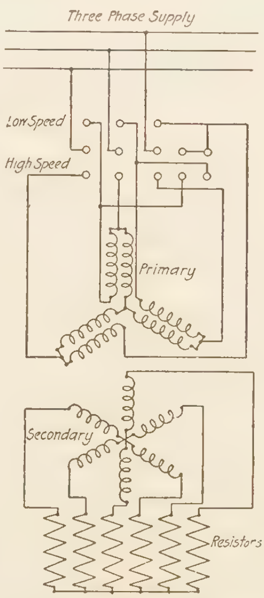


FIG. 67.—Arrangement of induction motor for two sets of poles.

This is used to give two efficient operating speeds for the induction motor.

Changes in Number of Poles.—The only type of motor which can be readily arranged to operate with varying numbers of poles is the alternating-current induction motor. The machine usually has a distributed primary winding; and it is possible, by proper interconnection of the coils, to change their grouping to give two definite numbers of poles, one of which is twice the other. One method of doing this is shown in Fig. 67. Also, on account of the construction of the primary, the coils being distributed in slots around the periphery, two or more distinct windings, each giving any desired number of poles, may be placed on the machine. Each of these may have its coils grouped to give two sets of poles in the ratio of 2 : 1, so that two windings may be arranged to give four sets of poles. The speed of an induction motor depends almost entirely on the frequency of the supply and the

number of poles, so that this combination would give four operating speeds. In order to make the arrangement available, it is also necessary to wind the secondary of the motor with the same numbers of poles as the primary. On account of the complication when several different windings are placed on the secondary, the usual limit is two numbers of poles. In case a squirrel-cage secondary winding is used, this restriction does not apply, and the same secondary will work fairly well for any combination. The squirrel-cage rotor is not very satisfactory for traction, and is seldom used.

Changes in Frequency.—The speed of an induction motor may readily be varied by changing the frequency of the supply circuit. This can be done only through the medium of a rotating frequency changer, so that it is not employed directly. It is possible, however, to use the induction motor itself in this capacity; and when there are two motors in the equipment this permits a method which is used to some extent for controlling the speed of induction motors for railway service. In this form the connection is known as "cascade control," "concatenation," or "tandem control."

Concatenation of Induction Motors.—If the rotor of an induction motor be held still, and an e.m.f. be impressed on the primary, an e.m.f. will be induced in the secondary in the same manner as in a stationary transformer. The frequency in the secondary will then be the same as that of the supply circuit. This secondary e.m.f. may be used for any purpose, the same as with the ordinary types of polyphase transformer. If the rotor be revolved *in the same direction* as the magnetic field, it will cut the flux at a lower rate, and the secondary frequency will be correspondingly reduced. If the speed of the rotor be increased to synchronism, the flux will not be cut at all by the conductors on the rotor, and its frequency will be zero. Between the limits of synchronous speed and standstill the frequency will vary directly as the drop in speed below synchronism, or the "slip."

The e.m.f. generated in the secondary may be used to furnish a second motor with electric power. If the first motor be run at *half speed,* the frequency of its secondary circuit will be exactly one-half that of the supply; and if the secondary have the same number of turns as the primary, its e.m.f. will be one-half the line potential. The two motors being electrically similar, and mechanically coupled together, so that they are forced to run at the

same speed (as, for example, two motors on axles of the same car) the power will be delivered by the secondary of the first motor at the *synchronous speed* of the second. Since an induction motor cannot deliver any power at synchronous speed, the second machine will not take any current from the first save for excitation, and the first motor in turn, having no current in its secondary but the magnetizing current for the second, will not deliver any power. The system is then in the same state of equilibrium as would be the case were the first motor running alone in synchronism. The speed of the combination in this condition is,

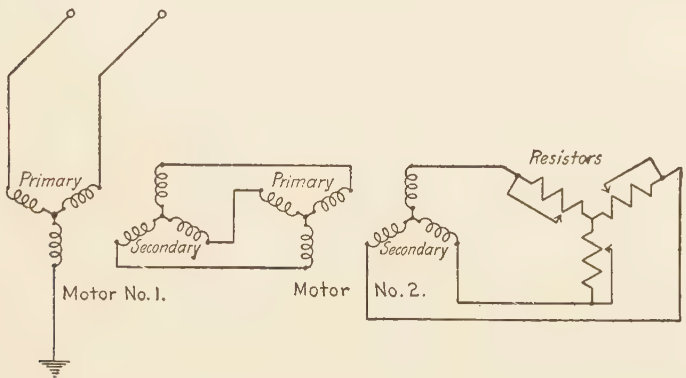


Fig. 68.—Connections for concatenation control of three-phase induction motors.

The secondary circuit of motor No. 1 is connected to the primary of motor No. 2, whose secondary is short-circuited through resistors. This arrangement gives an efficient half-speed running point, in which respect it is similar to the arrangement shown in Fig. 67.

however, exactly one-half the normal synchronous speed of the single motor.

If the speed of the motors falls a trifle, the frequency in the secondary of the first one is then slightly *greater* than one-half that of the primary, and the second will be operating *below* synchronism. The value of the slip of the second motor is the difference between the speed corresponding to the secondary frequency and the actual speed. Conditions are therefore right for producing torque in the second machine. This will cause a power current to flow in the rotor of the second motor, which in turn must be transformed from its primary. This power current must of course be drawn through the first motor, and the current in the secondary of the latter, reacting against its field flux, will produce a torque. It may be shown that approximately one-half the torque

is furnished from each machine. In order to obtain still lower speeds, as for starting, resistance may be introduced into the rotor circuit of the second motor. This will have the same effect as the insertion of resistance in the secondary of a single motor.

When it is desired to operate above the half-speed obtained with the two motors in tandem, the second one may be cut out of the circuit and the secondary of the first short-circuited, either on itself or through resistance, as necessary. The second motor, if wound for the correct potential, may be connected to the line in parallel with the first; but since the amount of power required for constant-speed running is considerably less than that for acceleration, the second motor is ordinarily left entirely out of the circuit, the power factor and efficiency of the single motor being higher than when the load is divided. This arrangement also makes possible a simpler form of controller.

In any case when motors are connected in cascade, the synchronous speed of the set may be determined from the fact that the effective number of poles of the combination is the sum of those of the two motors. For instance, if a four pole motor is concatenated with one having six poles, the result is the same as though a single motor with ten poles were used, whichever machine is connected to the line.

Split-Phase Control.—If a polyphase induction motor be connected to a single-phase supply, it will not have any starting torque, and will therefore remain stationary. If, however, the motor be started by any external means, it will continue to run and may be used in the same way as though it were operating on a polyphase circuit. Experiment has shown that this effect is due to a transforming action in the motor changing the single-phase supply to polyphase. If the terminals of the idle phase be tested, an e.m.f. will be found, substantially of the same value and in the same phase position as in regular polyphase operation. This e.m.f. may be utilized to furnish, with the single-phase e.m.f. of the supply, a true polyphase circuit on which may be operated standard polyphase apparatus.

If an induction machine of the type described in the last paragraph be placed on a locomotive, it is evident that a single-phase contact line may be used to supply polyphase motors for propulsion, as shown diagrammatically in Fig. 69. This method is used in one important installation in this country. The three-phase

induction motors may be of standard types, controlled by any of the means which have been described above.

Special Systems.—A number of special systems of operation have been tried at one time or another. All of them possess points of superiority, and may be used to advantage in certain installations. The most valuable of them are:

1. The "Ward-Leonard" system.
2. Permutator system.
3. Mechanical rectifier.
4. Mercury vapor rectifier.

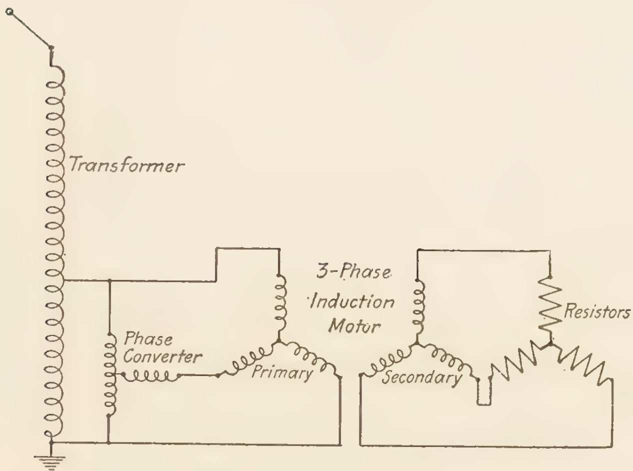


FIG. 69.—Split-phase control for operation of three-phase motors from a single-phase trolley.

By this means three-phase induction motors may be employed for railway service through the medium of the rotating phase-converter.

Ward-Leonard System.—This system of control, invented by the late H. Ward Leonard, is in its widest application suitable for use on any kind of supply circuit whatever. The current from the contact line is used to operate a constant-speed motor–generator set (Fig. 70), consisting of a motor suitable for the supply system, a separately excited direct-current generator, and an exciter, all mounted on the same shaft. The propulsion motors are permanently connected to the generator through the reverser, and operation is controlled by varying the potential. This may be done either by changing the resistance in the generator field circuit, or by varying the field current of the exciter.

The latter is the method usually recommended, since the loss is less.

This form of control can be operated to give absolutely uniform acceleration, and is applicable to any form of supply circuit. The efficiency during acceleration is high, since the rheostatic losses are practically eliminated. No contacts carrying heavy currents have to be broken or closed while the train is in operation, since the motor current can be reduced to zero by opening the exciter field circuit. The objection to the system is its great weight and cost. For this reason it never has been used in practice, and only a few locomotives have been equipped with it. Some recently adopted types of control would indicate that the

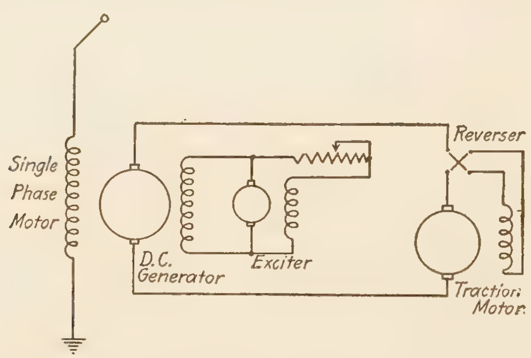


Fig. 70.—Ward-Leonard system of control.

This method is suitable for the operation of standard direct-current railway motors from a single-phase trolley, no matter what the frequency. A motor for operation on any commercial circuit may be substituted for the single-phase machine.

weight and cost of the Ward-Leonard system are not so excessive as would appear from the opinions of different engineers.

It should be stated in this connection that the Ward-Leonard control is used somewhat extensively for mine hoists and similar stationary service.

Permutator Control.—A special form of induction machine, known as the "permutator," has been brought out for transformation from alternating to direct current.[1] It consists essentially of an induction motor primary and secondary winding held stationary. The secondary winding is similar to a direct-current generator armature, and has leads brought out to a commutator. Since the secondary is held still with reference to the

[1] A more complete description of this machine is given in Chapter XIII.

primary, the e.m.f. generated by the former has a direct ratio to the line potential, as in an ordinary transformer. If a set of brushes be rotated on the commutator *at synchronous speed*, direct current can be taken off, and used to operate ordinary series railway motors. Any standard type of direct-current control may be employed, or the primary potential may be varied by taking different taps from the lowering transformer. A locomotive constructed on this principle has been operated in France for some time, and is said to be very satisfactory.

Mechanical Rectifier.[1]—In place of the permutator, a mechanical rectifier may be employed for furnishing the means of chang-

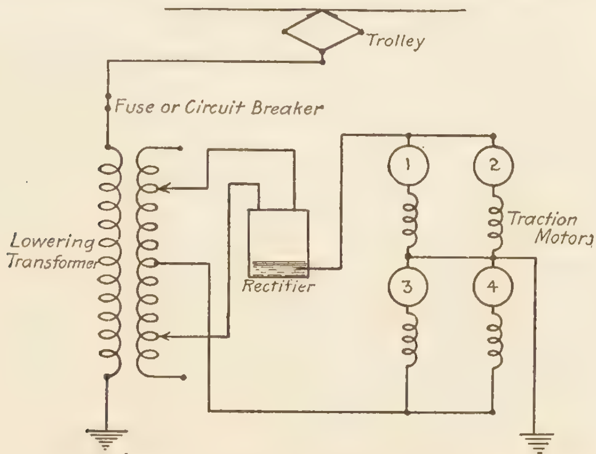


FIG. 71.—Mercury rectifier control.

With the mercury vapor rectifier, standard direct-current motors may be satisfactorily operated from a single-phase trolley. As shown, two 600-volt machines are placed in series, with the middle point grounded.

ing from alternating to direct current for supplying the propulsion motors. The rectifier is in effect a two-part commutator, rotated at synchronous speed by means of a small motor. The two main segments of the commutator are divided into several sections, and connected through reactance. This prevents the e.m.f. from dropping to zero while passing from one pole to the other. A locomotive has been built, using this method of operation, but no figures have been published which would indicate whether it has proved satisfactory or not.

Mercury Vapor Rectifier.—Still another system proposed for railway operation is to change from high-tension single-phase cur-

[1] See also Chapter XIII.

rent to direct current through the medium of a mercury vapor rectifier. Rectifiers of this type have been built commercially in large sizes, and are not by any means the delicate contrivances of several years ago.

During the year 1914, a trial equipment was placed in operation for the Pennsylvania Railroad on the single-phase line of the New York, New Haven and Hartford Railroad. This locomotive was equipped with standard direct-current motors, operated from a mercury vapor rectifier. The connections are shown in Fig. 71. Although detailed reports are not yet available, the equipment has been in revenue service for several months, and it is stated that the performance is exceedingly satisfactory. It is evident that this form of control is a commercial possibility; and if adopted will remove some of the limitations imposed on the single-phase system on account of its inability to use standard direct-current motors.

CHAPTER VI

POWER REQUIREMENTS AND ENERGY CONSUMPTION

Requirements of Train Operation.—In the engineering work necessary in connection with the design and operation of a railroad, it is essential that the amount of power demanded from the system, and also the amount of energy required for train movement, be accurately determined, whatever the character of the motive power. For any type of motive power, there are certain fundamental relations which determine these quantities; and from them the proper selection of equipment may be made. The consideration of these relations has already been made in Chapter II; they must now be brought together to see their connection in the solution of the problems at hand.

The quantities which have the greatest effect on train operation are its weight, the train resistance, both inherent and incidental, the acceleration and the maximum speed. These are the essential ones; but the length of run has a marked effect, since it may change the maximum speed or the acceleration.

The maximum speed attained affects the *power* required principally by the difference it makes in the train resistance, but its effect on the *energy* consumed is much greater, since it is a measure of the energy input.

The train weight is a determining factor in both power and energy, since the value of either varies directly with it.

It will be shown that the acceleration has a great influence on the *power* required, but its effect on the total *energy* is very small, save in an indirect way. This must be so, since the energy imparted to the train depends so much on the maximum speed attained during the run.

The inherent train resistance, while it has some effect on both the power and the energy, is in most cases small in comparison with other variables. The incidental resistance, especially that due to grades, may affect the requirements more than any other factor. This is seen most in operation of slow-speed freight trains, in which case the acceleration is relatively low.

In order to ascertain the power demand, then, for any specific case, it is necessary to know the values given above. The determination can be made by the methods outlined in Chapter II.

"Straight Line" Speed–Time Curves.—It is difficult to deduce an analytical relation between the variables entering into the power problem. The characteristic curves of motive powers vary in a manner difficult to express in a simple equation; and the same is true of train resistance. In a large number of problems a need is felt for a simple and reasonably accurate determination of power requirements. By making a number of approximate assumptions it is possible to use a graphical treatment which is comparatively simple.

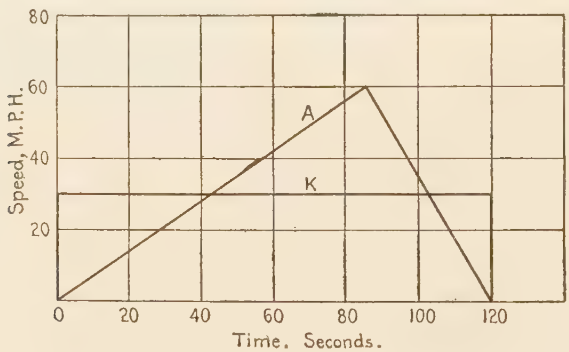


FIG. 72.—Simple straight-line speed–time curve.

If we consider the motive power to be such that it can supply a constant tractive effort over a limited range of operation, and assume uniform rates of coasting and of braking, the problem is reduced to a point where a solution becomes practical. The simplest run of this type (*A*, Fig. 72) consists of acceleration at a constant rate until it is necessary to cut off the power and apply the brakes. It is evident that if the rate of braking is the same for all runs, this gives the minimum possible acceleration. Further than this, an inspection of the diagram shows that the maximum speed is exactly twice the average speed. Comparing this run with the ideal run *K*, at average speed, it will be seen that the distance covered is the same in each, the area of the two diagrams being the same.

If a higher rate of acceleration than the minimum be used, it will be necessary, in order to cover the same distance in the same time, to introduce a period of coasting (Fig. 73, run B). Such a high maximum speed as in run *A* (which is reproduced from Fig. 72) will not be attained, since the train is propelled at nearly the maximum speed for some time by coasting. With still higher rates of acceleration (runs *C* and *D*) the maximum speed is further reduced. In certain runs, if the amount of drifting is too great, the velocity which the train must reach will again be increased, on account of the great reduction of speed while coasting. In general, the efficiency of the motive power remaining the same, the most effective run for covering the given distance is that in which lowest value of crest or maximum speed is attained.

The method outlined in the last paragraph shows a way of determining the most economical acceleration for any given run.

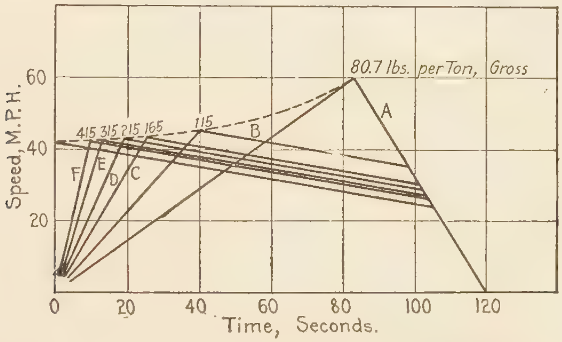


FIG. 73.—Influence of acceleration on speed–time curve.

If a succession of identical runs is taken as the required service, one acceleration can be found which is most efficient for all of them. When the runs differ, the best average rate can be used. This acceleration having been chosen, it should be used for all runs, no matter what their length.

Speed–Time Curves with Electric Motors.—When we consider applications of the straight line speed–time curve, we find that in most cases of practical motive powers, the assumed conditions cannot be exactly met. In using electric motors, the uniform acceleration can be adhered to only while the potential is being raised. After the motors are operating directly on the line there is no possibility of continuing the maximum acceleration; but the tractive effort will fall off as determined by the characteristic curve of the particular machine used. If the run is short, this

will not make a marked deviation from the straight line curve, so that for preliminary estimates or for analytical study the approximate method remains useful. For the actual selection of equipment for any individual case the motor characteristics must be employed. The method used for determining the speed–time curve is that described in Chapter II, page 39, or any other accurate way of plotting it. In order to estimate the distance covered by the run, the distance–time curve may be obtained by the use of the integraph, by successive partial integrations, or by determination of the distance increments from the data used to plot the speed–time diagram. Curves of this character are of the greatest value, since they show the exact distance covered by the train at any portion of the run.

Current–Time Curves.—After the speed–time curve for any run has been plotted, the current–time curve may be found directly, since there is a definite relation between the speed of a motor and the current passing through it, which is invariable. This may be seen at once by an inspection of Fig. 19. It must be remembered, however, that while the motors of an equipment are running at reduced potentials, or under other abnormal conditions, the relation between speed and current will not be the same as for normal operation, although easily found at such times by the methods already given. The current–time curve may then be plotted. This curve is of value, as indicating the load which is being demanded from the line, as well as that which is being imposed on the motors.

Power–Time Curves.—If the line potential is constant, the current curve gives a measure of the power drawn from the line at any instant, and *its integral measures the amount of energy used* for the run. By this means the performance of different trains or of different runs may be compared. If the line pressure is variable, the power–time curve must be obtained as the product of the current curve and the pressure. In that case a graph of the latter should be plotted against time.

Use of the Current and Power Curves.—This series of curves is of great use to the engineer in determining the size of equipment necessary for the generating and substations of a road, and for the size of transmission and feeder wires. For this purpose current–time or power–time curves must be plotted for a day, or such other period as covers the entire range of load. The sum of the instantaneous current values gives the total demand on the

power plant at any given instant; so by a process of summation the actual load curve for an entire day's run or any desired time is determined. A study of the territory in which the road is located will, in conjunction with the current or power curves for individual trains, give an opportunity for dividing the line into proper sections for the location of substations. This will be considered at greater detail in a later chapter.

Motor Capacity.—The other great use of the current-time curve is in the determination of the capacity of the motors to be used for a particular purpose. There are several different methods of doing this. Of these, the most direct is that in which the motor heating is ascertained from the current and potential carried by the motor during the period which the rating covers.

The ability of a motor to carry load depends on several different things: the form of the characteristic curves must be correct, and operation not extended beyond their proper range; the temperature must not exceed some maximum value, as determined by the materials of which the machine is constructed, and the motor must not be worked beyond the limits of commutation. In modern, well-built motors, the characteristic curves continue of proper shape beyond the ordinary range of operation, and the commutation, both in direct-current and single-phase railway motors, is so good that it need not be a determining factor. The heating of the motor parts stands as the practical limit, both for instantaneous and for sustained loads. Modern motors are usually constructed of fireproof material, the only non-metallic parts being the insulation, which consists very largely of mica, asbestos and other heat-resisting substances.

Heating Limits.—Heating of the motor imposes limits of two kinds to its capacity: instantaneous or momentary, and continuous. If a sudden load is placed on a motor, there is a rush of current, with a consequent I^2R loss in all portions of the circuit. If the loss is sufficient, it may cause overheating of some part, and burn out the winding at that place. Or it may be great enough to melt one or more of the soldered connections and open the circuit, with the possible formation of an arc. Even though the joints in modern motors are all made with high-grade tin solder, it sometimes happens that an overload is so heavy as to melt the solder at the commutator necks. The natural safeguard against such damage is to place in the motor

circuit an automatic circuit-breaker, or a fuse, set so as to open before the motor is damaged.

The other heating limit is the one on which the normal rating is based. Any electrical apparatus has a certain loss in converting energy from one form to another; and it is this which, occurring within the machine, causes heating. Motor losses have already been discussed in Chapter III. Some of them are dependent on the current, others on the potential, and still others on the speed of rotation. In general, however, the losses may be grouped into two classes: those which are a function of the current, and those dependent on other relations. Those losses due to the current vary nearly as its square; the remainder about as the first power of the terminal pressure. To get the average loss for a given run will be to determine the corresponding rate of heat generation, and hence gives a means of finding the capacity of the motor.

In this country, railway and other motors for intermittent service are rated in two ways: by the load they can carry for one hour or other stated time with a given temperature rise, under specified conditions, and by that which they can carry continuously with the same temperature rise, under other stated conditions. Either method assumes that the load will be uniform during the period for which the rating is made.[1]

Character of Railway Motor Load.—In general, it is not possible to maintain the load on any machine at a constant value in service. In the case of a railway motor, its function is to start a train from rest, accelerate it to some operating speed, and run it at that speed for a greater or less time. After this the power is cut off, the train allowed to coast and finally come to rest under the action of the brakes.

An inspection of the load curve shows that the current through the motor is never constant, unless the run is so long that the speed continues at the maximum for some time. It is not possible to assign any average value to it offhand. Furthermore, there is a period in every run where the motors are not in operation, a portion of it being while the train is in motion and the remainder while it is standing still.

After making a stop of limited duration, a similar cycle ensues; and this will be repeated indefinitely during the entire time of

[1] The accepted method of rating railway motors is given in the *Standardization Rules* of the American Institute of Electrical Engineers, 1914 edition.

operation, as for a round trip, or more frequently a whole day's run. The succeeding cycles of current may not be precisely the same, since the length of individual runs, the maximum speeds possible, and the physical limitations of grades, curves and wind may vary. But the general nature of the cycle remains the same in all cases. If it is desired to depict the performance of a railway motor, it is necessary to plot a series of current–time curves for a long period of operation, say for a round trip. Such a current–time curve is shown in Fig. 74.

Methods of Equating Motor Load.—In order to use the data from the actual operation of the motors, as determined by the current–time and power–time curves, it is necessary to find some basis on which they may be equated to constantly applied loads. This is essential both for purposes of testing and for the proper selection of motors for a given service. The oldest way was by comparison, an equipment being selected for a proposed road because it had given satisfaction in a similar service, possibly in another locality. Although this method is crude, it was used for want of a better, and it must be admitted that very good results have been obtained.

The scientific method of getting the equivalent rating is to determine the potential and current which, constantly applied, will produce the same load on the motor as the variable one obtained in service. Since heating is the principal condition which determines motor capacity, it is evident that at the equivalent load it must be the same as that in service. The determination of this load depends on the use of a method which will find the proper relations between the variable current and potential and their equivalent constant values to give the same heating in the motor.

Heating Value of the Current.[1]—In any electric circuit, there is a certain loss due to the passage of the current through resistance. This loss is a function of the current, the time, and the resistance. It is always proportional to the square of the instantaneous value of current, i, into the resistance in ohms, r, being numerically equal to i^2r.

With the current remaining constant at a value I for any definite interval of time, as

[1] This discussion follows the method of C. O. Mailloux, "Methode de determination du courant constant produisant le même échauffement qu'un courant variable," *International Electrical Congress*, Turin, 1911.

$$t = t_1 - t_0$$

the amount of energy, W, dissipated as heat in the resistance r is

$$W = I^2r\,(t_1 - t_0) = I^2rt \qquad (1)$$

When the current varies during the time considered the loss becomes, calling the instantaneous value of current i,

$$W = \int_0^t i^2rdt \qquad (2)$$

If the resistance loss is the same in the two cases, we may equate the expressions (1) and (2):

$$W = I^2rt = \int_0^t i^2rdt \qquad (3)$$

from which we may determine

$$I^2t = \int_0^t i^2dt \qquad (4)$$

$$I^2 = \frac{1}{t}\int_0^t i^2dt \qquad (5)$$

$$I = \sqrt{\frac{1}{t}\int_0^t i^2dt} \qquad (6)$$

Equations (5) and (6) give the important relations between the equivalent constant and variable currents producing the same heating in the same time interval. From equation (5) it may be seen that their *squares* are equal, and equation (6), that the so-called "effective" current is equal to the square root of the mean of the squares of instantaneous values.

The problem of equating a variable current to a constant one thus resolves itself into finding an effective value which is numerically equal to the square root of the mean of the successive ordinates of the curve representing the function $i^2 = f(t)$. If the equation of this function is known, the determination is simple; but if, as is usually the case, it cannot be obtained, some approximate construction must be resorted to.

Determination of Effective Current from I^2 Curve.—The general form of the graph of current as a function of time is shown in Fig. 74, which represents a curve of this character. Such a chart may be drawn by a recording ammeter, or by taking a large number of successive readings and plotting the curve therefrom.

To apply the method indicated by equation (6) for getting the equivalent current, the values of i in the current–time curve must be squared and re-plotted, as shown in Fig. 75. The more rapid the fluctuations of the original curve, the closer together the

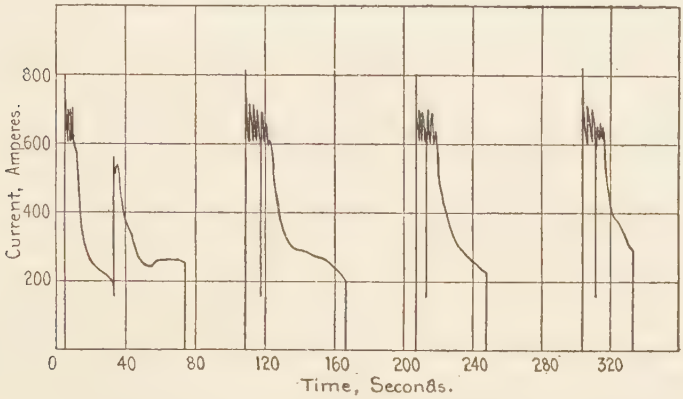


FIG. 74.—Typical current–time curve.

This represents the actual form of curve obtained in rapid-transit service with frequent stops.

points should be taken, since the effect of squaring is to greatly magnify the differences between succeeding values.

The area under the curve, as Fig. 75, must next be found by some form of mechanical integration, as the use of a planimeter.

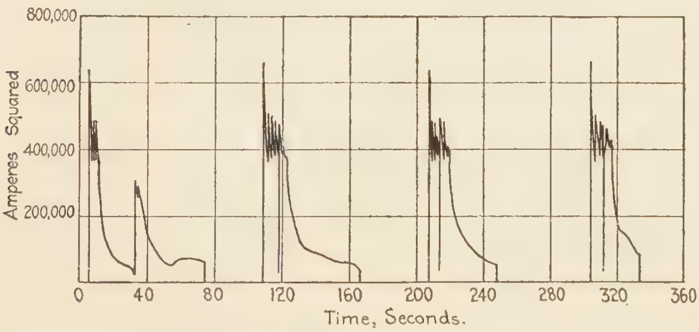


FIG. 75.—Current squared-time curve.

This curve is produced by squaring the values of the current shown in Fig. 74.

This area, divided by the total length of the diagram, gives the mean ordinate, I^2. It is necessary to use the same units of linear and square measure, for, if the planimeter gives the area in square

inches, the length of the base should be taken in inches, and the quotient will give the average height in inches. This is sometimes forgotten in interpreting the results. The square root of this mean ordinate, when reduced to the scale of the curve, is the effective value desired, as I in equation (6).[1]

Determination by Polar Method.—The second method, which was elaborated by Mr. Mailloux in the paper above referred to

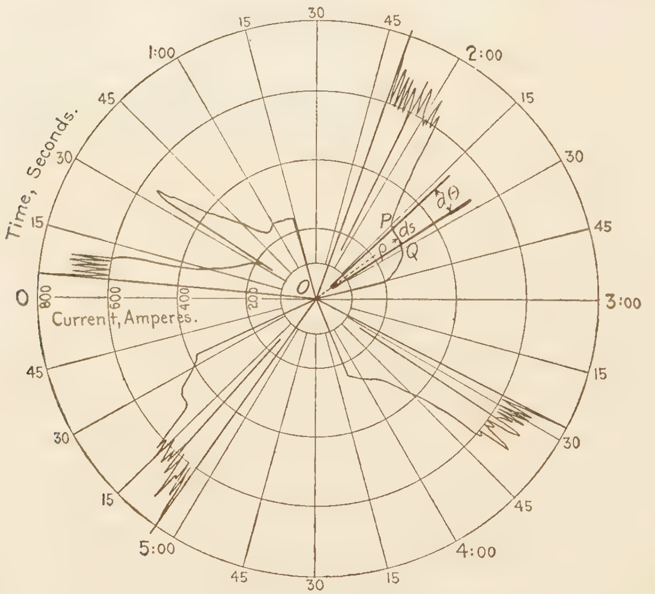


Fig. 76.—Polar current–time diagram.
This represents the same function as Fig. 74, but replotted in polar coördinates.

obviates the necessity of plotting a curve of values of current squared, replacing it by a polar diagram of current, Fig. 76, which, while giving the same final result, is simpler to construct.

The use of the polar curve for finding the heating due to a current originated with Dr. Fleming,[2] who employed it for determining the effective value of the alternating current. The method of Mr. Mailloux is based on the same principles, but is wider in scope, including the evaluation of any currents, as indicated in equation (6).

[1] See A. M. Buck, "Some Graphical Solutions of Electric Railway Problems," Bulletin 90, Engineering Experiment Station, University of Illinois. A simple graphical method of determining the current-squared curve is given in Chapter X.

[2] J. A. Fleming, "*The Alternate Current Transformer*," 1896, Vol. I, §32, pp. 190–194, "Representation of Periodic Currents by Polar Diagrams."

The first step in this method consists in plotting the current-time curve on a polar basis, as shown in Fig. 76. In doing this the current, i, being the independent variable, is made the radius vector, and the time, t, becomes the angle.

To make the transformation of coördinates complete, the following condition must be met, and that only:

$$f(n\Delta t) = f(n\Delta \theta) \tag{7}$$

for all values of n included between the limits $n = 0$, and $n = \dfrac{t}{\Delta t}$, when t is the total length of the diagram in rectangular (or any form of Cartesian) coördinates. If this requirement is met, an ordinate y of the rectangular curve, at any distance from the origin along the X-axis and represented by $n\Delta t$, will always be equal to the radius vector, ρ, of a polar curve, situated at a proportional angular distance, by $n\Delta\theta$. It may be seen at once that this relation is independent of the values given to Δt or to $\Delta\theta$, proportional changes in these affecting only the scale of the curve.

The polar curve has different properties from the rectangular curve; since it is this difference which is utilized, the characteristics of the polar curve must be determined. Of these, the most important for the present purpose is the area included by the curve. An element of the polar diagram contained between two radii vectores, OP and OQ (Fig. 76), has an area dA,

$$dA = \tfrac{1}{2}\rho ds = \tfrac{1}{2}\rho^2 d\theta \tag{8}$$

ρ being the radius vector, $d\theta$ the vectorial angle, and $ds = \rho d\theta$ any element of the curve. When the entire vectorial angle included is

$$\theta = \phi_1 - \phi_2$$

the area, A, is equal to

$$A = \int_0^\theta dA = \tfrac{1}{2}\int_0^\theta \rho^2 d\theta \tag{9}$$

This area may be found by mathematical substitution, where practicable, or by mechanical integration in any case, as by the use of the planimeter.

For polar curves, as for Cartesian curves, there may be found an equivalent area which corresponds to a constant mean height. Using this ordinate and the same total vectorial angle, a polar diagram will be obtained having the same area as that included by the actual curve. In Cartesian coördinates this equivalent diagram is a parallelogram; in polar, the sector of a circle.

The area of the equivalent sector, with a vectorial angle θ, and mean ordinate I_p, being represented by A, we have

$$A = \frac{I_p{}^2\theta}{2} \tag{10}$$

Equating this with equation (9),

$$A = \frac{I_p{}^2\theta}{2} = \tfrac{1}{2}\int_0^\theta \rho^2 d\theta \tag{11}$$

from which is reduced

$$I_p = \sqrt{\frac{1}{\theta}\int_0^\theta \rho^2 d\theta} \tag{12}$$

A comparison of equations (6) and (12) shows them to be of precisely the same form. The two equations, one in Cartesian coördinates, and the other in polar, give two ways of obtaining identical results. Using both methods for the solution of the same problem, we may say that $I = I_p$, so that

$$\sqrt{\frac{1}{t}\int_0^t i^2 dt} = \sqrt{\frac{1}{\theta}\int_0^\theta \rho^2 d\theta} \tag{13}$$

Although the result reached by equations (6) and (12) is the same, there is the important difference that while equation (12), or the member to the right of the equality sign in equation (13), is the *mean ordinate of a polar curve*, equation (6), or the left of equation (13), does not represent the mean ordinate of the curve of squares, but the *square root* of that value. The mean ordinate, I^2, of the curve of squares in rectangular coördinates, i^2, is given in equation (5). It may be accounted for by squaring both sides of equation (13), which gives

$$\frac{1}{t}\int_0^t i^2 dt = \frac{1}{\theta}\int_0^\theta \rho^2 d\theta \tag{14}$$

Referring to equation (5), and substituting, we have

$$I^2 = \frac{1}{\theta}\int_0^\theta \rho^2 d\theta \tag{15}$$

I^2 represents the mean ordinate of the rectangular curve of squares of the function i. At the right of the equation is the correct equivalent of $I_p{}^2$, as may be seen by reference to equation (11). In other words, *the mean ordinate of a curve of squares in Cartesian coördinates is equal to the square of the mean ordinate of the polar*

curve representing the same function. It may equally well be stated that the mean ordinate of the polar curve of a function, being the radius of a sector subtending the same vectorial angle and enclosing the same area as the curve, is equal to the square root of the arithmetical mean of the squares of the ordinates of the same function, either represented by the polar curve itself, or by the corresponding curve in rectangular coördinates.

The expression just derived is general. The value of t, as used in equation (6), may be anything; the length of the diagram is hence indefinite, whether plotted in rectangular or in polar coördinates. The radius vector ρ may make less than one, or any number of, revolutions about the pole. If the vectorial angle is equal to 2π, the radius vector has made one complete turn.

As the length of the rectangular diagram is increased, the vectorial angle becomes correspondingly larger. The scale chosen for the polar diagram may be anything convenient, and the radius vector may make any required number of turns. In order to prevent confusion, it is preferable to use a distinct pole for each revolution of the radius vector.

Replacing in equation (15) the value at the right of equation (10), we have

$$I^2 = \frac{2A}{\theta} \qquad (16)$$

or, equally well,

$$I_p^2 = \frac{2A}{\theta} \qquad (17)$$

The square root of this expression is

$$I_p = \sqrt{\frac{2A}{\theta}} \qquad (18)$$

This equation indicates a practical method for finding the value of I_p, the mean ordinate (mean radius vector) of the polar curve.

The area, A, of a polar curve may be obtained readily by a planimeter. The value of θ, the vectorial angle, must be numerically equal (*i.e.*, in radians) to the number of times 2π that the radius vector has made turns around the pole.

To use the polar method of evaluating the motor load, the current-time curve must be re-plotted with polar coördinates. The simplest method is to keep the scale of ordinates (amperes) the same, and use any convenient value of angle to represent the

abscissa (time). As has been shown, the latter scale is immaterial; and the total vectorial angle may be so chosen as to make the transformation easy. For example, the use of 1° of angle to represent 1 second of time, or other simple relation, makes the construction of the polar diagram easy, since ordinates of the rectangular curve may be transferred directly with the use of dividers, no computation being required. Having transformed the curve into polar coördinates, the area may be found with a planimeter or by any other available method. This quantity must be substituted in equation (18) to get the value of I_p. It must be remembered that the vectorial angle must be taken in radians. The final result in amperes is found by multiplying the value of I_p by the scale of the curve, based on the units in which the area is determined. For example, if the area is found in square inches, I_p will be in inches, and the result must be multiplied by the number of amperes per inch to get the value of the r.m.s. current.

Average Motor Potential.—In any run with a normal set of motors, the train starts from rest, and is brought up to about half the maximum speed at a nearly constant value of current. This is accomplished by operating at reduced pressure during the accelerating period. It is evident that the average potential on the motor must be less than that of the line for the time during which the motor is receiving power. There is also a period when the motor is not connected, and hence is not subject to any e.m.f. whatever. The iron loss, and to some extent, the friction and windage, are dependent on the value of motor potential. These losses do not vary as a direct function of the pressure, but, on the contrary, are nearly the same over a wide range. For this reason it has been found sufficiently accurate to obtain them for a few different average values, such as one-half, three-quarters and full potential. Generally speaking, the capacity of the motor to get rid of heat determines the temperature to which it will rise with a certain amount of loss. This temperature is largely independent of where the losses are produced; that is, if their sum is a certain total, and corresponds to a definite temperature rise, the same temperature will be reached if the distribution of loss between its various components is changed. Since the copper loss is a function of current only, it can be found by the method outlined. The iron and friction losses are more complex, and cannot be obtained readily except by actual

test. They do vary with the terminal potential, although not in direct proportion. It is evident, then, that if a motor is able to carry I amperes at E volts with the specified temperature rise, it will only carry a *less* current, I', at a *higher* potential E' depending on the amount of increase in the iron and friction losses. That the variation in these losses with the potential is comparatively small may be seen by reference to the motor whose curves are given in Fig. 19. This motor has a continuous capacity of 60 amp. at 300 volts, or of 55 amp. at 400 volts. A small error in the determination of the average potential will therefore cause a relatively slight discrepancy in this connection.

Rating of Railway Motors.—When the heating value of the current has been determined, it furnishes a basis for finding the constant load which should be applied to a motor for purposes of test; or, conversely, that current which the motor can carry on test represents the effective value of the variable current which may safely be allowed in actual operation. In making tests at the factory, at least two separate determinations are made: the current which the motor can carry for one hour at normal potential to obtain the maximum allowable temperature at the end of this time, and that which can be applied continuously, either at the line pressure or some lower value, to give the same maximum temperature.

The rating of railway motors has been open to considerable discussion, on account of the difficulty in specifying the average or effective load (see paragraph on "Heating value of the current"). Various ways of determining the capacity have been advanced at different times, but none of them has proved entirely satisfactory. The present method of rating, adopted by the American Institute of Electrical Engineers in 1914,[1] is as follows:

"**415. Nominal Rating.**—The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90° C. at the commutator, and 75° C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to

[1] Standardization Rules of the American Institute of Electrical Engineers, *Proceedings* A. I. E. E., Vol. XXXIII, p. 1281, August, 1914.

secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100° C.

"**416.** The statement of the nominal rating shall also include the corresponding voltage and armature speed.

"**417. Continuous Rating.**—The continuous ratings of a railway motor shall be the inputs in amperes at which it may be operated continuously at one-half, three-quarters, and full voltage respectively, without exceeding the specified temperature rises (see §420), when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the volume of air on which the rating is based shall be given."

The first, or nominal rating, is the one which has been used for many years in this country as expressing the output of a railway motor. It is not an indication of the load that the motor can carry in service, and is of value mainly to give a general comparison of the capacities of various machines. The second, or continuous rating, does give an indication of the ability of a motor to perform a specified service, and is the one which can be employed to advantage in the selection of equipment.

It is to be noted that the continuous rating, as given in the definition, includes provision for consideration of the method of ventilation used. This feature is very important. The capacity being dependent principally on the heating, the motor will have a temperature rise at any specified load which is determined by the rate of generation of heat due to losses in the machine, and the ability of the motor to get rid of the heat thus produced. With natural ventilation, the air coming in contact with the outside of the motor case constitutes the only medium available for this purpose. If, by any means, the quantity of air passing over the motor case is increased, the amount of heat given off will be greater, and the temperature of the motor reduced. Even if no ventilating system is provided, the rapid change of air under a moving train will cause the motor to operate at a lower temperature than when tested in a factory in still air. With special methods of ventilation, in which a quantity of air is forced through the motor, the temperature at the specified load is still further reduced. It follows that with any system of artificial ventilation the rating, either nominal or continuous, can be increased. In the rule for determining the nominal rating it is expressly

stated that no external ventilating system shall be employed, so that the gain in capacity applies only to the continuous rating.

In some recent types of railway motors, the ventilation has been improved by the addition of blowers on the armature shaft, arranged to pass a comparatively large amount of air through the case (see Chapter IV). With motors of this type the ventilating system is an integral part of the machine, so that the advantage is not confined to the continuous rating, but also serves to increase the nominal rating. Since the latter is useful for comparison only, this method of ventilation has the effect of apparently giving a motor a higher one-hour capacity than when the ventilating system is outside the machine itself.

Motor Capacity and Selection.—To use the above information in the selection of a motor for a definite service, it is necessary to determine the average current and potential for the equipment. This may be done by finding the average run, and plotting for it the current curve for a motor which is expected to do the work; or by making a set of current curves representing the performance of the motor over an extended series of runs, and getting the average current from them. In either case the "root mean square" (r.m.s.) current should be found, which gives the load which the motor will have to carry. If this current is equal to the continuous rating of the motor at the average potential found for the run or runs, the motor has sufficient capacity for the work, unless it is considered advisable to have a certain margin for handling emergency business, as for hauling trailers. If the r.m.s. current is decidedly less than the continuous rating, it will be well to see if a smaller motor can be used. If, on the other hand, the r.m.s. current is greater than the continuous capacity, a larger motor will be needed. It is never wise to attempt to load a motor beyond its continuous rating, since there is great liability of permanent injury. Practically any railway motor of standard make is able to carry its rated continuous load without difficulty, and will operate indefinitely without trouble if this is not exceeded. But if the best of motors is loaded beyond the continuous capacity, trouble is liable to develop, armatures to burn out, commutators become rough, etc.

Motor Speeds and Gearing.—For the smaller motor equipments, such as are used on city and interurban cars, the motors are almost invariably of the geared type. There is considerable latitude in the choice of gear reduction for any particular service.

Reference to the section on "Straight Line Speed-Time Curves" at the beginning of this chapter will show that the same run can be covered in a given time with a wide range of acceleration rates. Since it has been demonstrated that there is a certain acceleration rate which is most efficient for a given run, this should be determined and the motor gear ratio selected to give it. In nearly all practical runs this will call for the maximum acceleration possible; or, in other words, the motors should be geared for the lowest speed which will enable them to cover the distance in the given time. A higher speed will be accompanied with lower acceleration and less coasting; and since the kinetic energy of the train is being used for propulsion when drifting, the motors are not called on for so great a load. This is beneficial, both from the standpoint of motor capacity and of energy consumption. In addition, the required acceleration may often be obtained with less current from the line, so that the demand on the electrical system, and the transmission and conversion losses, are reduced.

For interurban cars, the same equipment is ordinarily used both for local and for limited trains. If the gearing is correct for the local runs, the maximum speed possible is ordinarily too low to meet the demands of the fast schedule needed for limited trains. If the motors are geared for the high speed demanded in limited runs, the possible acceleration for local service will not be enough; or the heavy current will be so great as to cause overheating. Some roads have used motors with a greater capacity than otherwise necessary in order to standardize the equipment.

Use of Field Control Motors. A more recent solution is the use of field control motors, such as described in Chapter III. With the heavy field the tractive effort is sufficient to meet the demands for rapid acceleration in local service, and for the city portion of limited runs. The weak field allows the same motors to be operated at high speeds for the limited trains, and for the longer runs in local service. Both of these results may be accomplished with motors of the minimum possible size, while the power demand from the line is kept down to as low a value as with the single-speed motor suitable for the same service.

Proper Number of Motors.—A question to be decided in the choice of motive power is that of the number of units to be used to produce the desired results. It is obvious that if the proportional performance of motors of all sizes were the same, it would

make no practical difference into how many units the power were subdivided. In practice, with double-truck cars, there is a choice between two motors and four motors for the equipment. The capacity of electric motors varies nearly as the fourth power of the linear dimensions, so that a motor of double rating will have its dimensions approximately 1.2 times those of the smaller machine, resulting in less total weight for the two-motor equipment. Since the dimensions are not increased in proportion to the output, the length of windings and of the magnetic circuit are correspondingly less, and the efficiency is consequently higher. All other things being equal, the use of two motors of a certain rating should result in a smaller input to the car than when four motors of the same total capacity are employed. From the efficiency standpoint there can be no question but that the smaller number of motors is preferable. This arrangement also has the effect of simplifying the control wiring, and in some cases allows a less intricate and cheaper controller.

The use of four motors is defended on the ground that there is greater reliability with this combination, since the damaging of one motor only affects one-fourth of the total number. But in ordinary types of series-parallel control the motors are permanently connected in pairs, so that when one is injured its mate has to be cut out at the same time. Neither is it at all certain that four machines, with the necessary duplication of parts, both in the motors themselves and in the control and wiring, are less subject to damage than the two larger ones which are their equivalent. It is evident that the maintenance expense for the four machines will be greater than for the two. The cost of repairing does not vary much with the motor capacity; and, with equal wear, there are twice as many parts to renew in the four-motor equipment.

The best reason for the use of four motors is that the entire weight of the car is available for adhesion, so that the maximum tractive effort possible with a four-motor equipment is greater than with two motors. If the car alone is considered, the use of all axles as drivers gives a total adhesion, depending on the condition of the track, of from 500 lb. per ton with a coefficient of 25 per cent. to 200 lb. per ton with one of 10 per cent. Even in the worst cases, with wet and slippery track, it is possible to get an acceleration of approximately 2 miles per hr. per sec. With the two-motor equipment about 60 per cent. of the total

weight of the car is on the drivers. The corresponding values of maximum tractive effort available are from 300 lb. per ton with an adhesion coefficient of 25 per cent. to 120 lb. per ton with one of 10 per cent. With the worst conditions such an equipment should be able to give an acceleration of about 1.2 miles per hr. per sec. This might not be high enough for an extreme case, but in general is sufficient. If the motor car is to haul one or more trailers the use of four motors is entirely justified.

Another place where the use of four motors is advantageous is where the total motor capacity is so great that the limit of space between the wheels and beneath the car floor is reached. It is quite practical to build a single motor of about 180 kw. capacity of such dimensions that it can be mounted on a car truck for standard gauge track, with 36-in. wheels. It is seldom that a greater total capacity than 360 kw. per car is needed, so that this limitation is not felt except in the design of locomotives.

It should be noted that with maximum traction trucks[1] the proportion of total car weight which can be placed on the drivers is increased from 60 per cent., as given above, to from 75 per cent. to 80 per cent. Such trucks are used to a considerable extent in city service, but are unsuited to speeds much over 30 miles per hr., so that their application is confined to special cases where this speed will not be exceeded.

Power Required for Alternating-Current Motors.—The foregoing discussion has been made with special reference to direct-current series motors, but in nearly every particular it applies equally well to both single-phase and three-phase motors. The method of determining the capacity is precisely the same for any type of motor; and the ways of increasing the continuous rating by improving ventilation may be applied equally well to all. The relative performance of two-motor and four-motor equipments is identical, whether the machines be designed for operation on direct current or on alternating current. Curves showing typical results for a run with single-phase series motors are given in Fig. 77.

It has been mentioned previously that field control is not practical with single-phase series motors; nor is it necessary, since the speed may be varied by the use of different taps on the transformer.

[1] See Chapter VIII.

Alternating-current motors, as now built, are not usually employed for such high rates of acceleration as are direct-current motors; but this is largely because the demand for alternating-current distribution is almost entirely in a field where the required acceleration is much lower than in city service. It is quite possible to obtain the same acceleration with either type of motor.

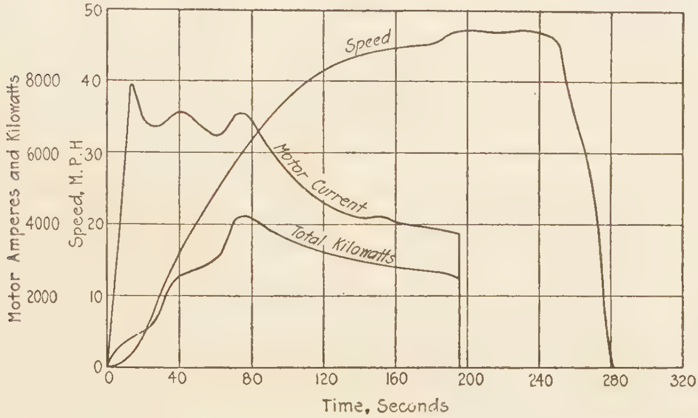


FIG. 77.—Speed–time and input curves with single-phase motors.

The effect of the transformer control is shown in the low value of *power* input during the period of sub-normal potential. Contrast this with Figs. 47 and 48.

Energy Required for Train Operation.—We have seen in the preceding paragraphs that a certain amount of force is necessary for the propulsion of trains. Since the application of force results in the performance of work, a certain amount of energy is required for train movement, which can be determined from the mechanical relations taken up in Chapter II. The energy required may be divided into two kinds, as follows:

1. Energy which is not capable of return to the supply circuit, nor of use in the propulsion of the train.
2. Energy which can be recovered, in whole or in part, and used for propulsion, or returned to the supply system.

The energy under the first head consists of that used to overcome fixed resistances of all sorts. This includes both the inherent train resistance and that due to curves and natural winds. Losses in the motive power are also of this type.

The second class includes the energy for ascending grades and that needed for the acceleration of the train. Energy of this sort is stored in the moving body, either as kinetic or as potential energy.

In general, a large share of the stored energy is wasted in normal train operation. It is inexpedient for a train to descend a grade at too high a speed; so that, if it has been accelerating due to the force of a grade which has been previously ascended, this acceleration must often be stopped by the application of the brakes before the maximum attainable speed is reached. The energy of the grade is then dissipated in friction of the brake shoes against the wheels, and is lost. The kinetic energy of the train, due to its motion ($\frac{1}{2}Mv^2$) can be recovered and used for propulsion, if it is allowed to "coast" or "drift" after the power has been cut off. The speed will be reduced only so fast as energy is taken out of the train to overcome the resistances, so that the retardation will be slight. In ordinary operation it would be impossible to allow a train to coast to a standstill. In this case application of the brakes will prevent the return of energy. Generally speaking, then, a certain amount of energy due to the ascent of grades, and to the inertia of the train, is converted into useful work when descending, and in coasting to a reduced speed before the brakes are applied.

Kinetic Energy.—Since the kinetic energy of a moving body is proportional to the square of its velocity, the amount of energy which must be supplied to a train to accelerate it varies as the square of the maximum speed attained during the run. If no energy were wasted in train resistance, motor losses, etc., the minimum input would be taken by that run having the lowest maximum speed. The limiting condition would then give us a run with infinite acceleration to the average speed, constant-speed operation throughout the run, and finally infinite retardation to a stop at the end of the run. Such operation is manifestly impossible, since there is a limit both to the acceleration and to the retardation. Also, train resistance prevents motion at constant speed without the application of power, except under certain conditions. The variable character of the force exerted by ordinary forms of motive power complicates the problem still further, so that no general equation covering all cases is possible. Partial solutions have been made at various times.

Use of Straight Line Speed–Time Curves.—A reference to Fig. 72 shows that by considering, as in the determination of power requirements, that the motive power can supply a constant tractive effort for a limited range of speed, and that the train resis-

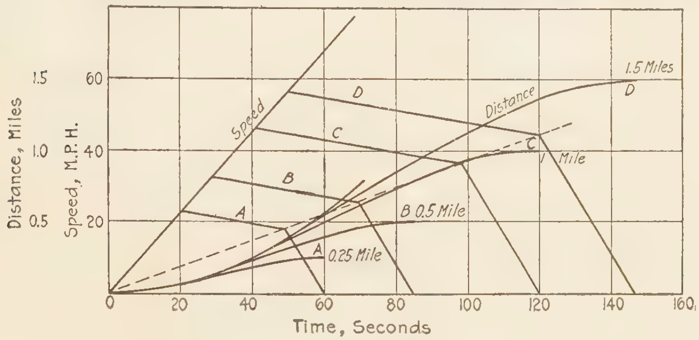


Fig. 78.—Use of the type run.

tance and braking rate are constant, we can use the straight line speed–time curves for a consideration of the energy consumption. Since the energy required for acceleration is stored in the motion of the train, the total amount required for this purpose varies as

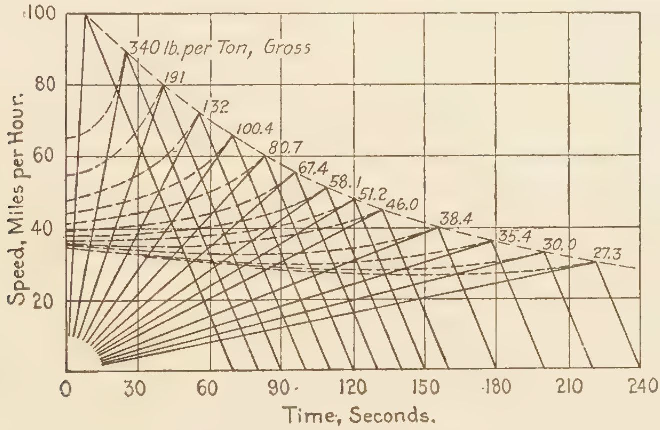


Fig. 79.—General locus of straight line speed–time curves.

the square of the maximum speed attained. If the minimum acceleration is used, as in Fig. 72, the energy imparted to the train due to its velocity must all be absorbed by the brakes when the train is stopped. If higher accelerations are employed, as

in Fig. 73, the maximum speeds are reduced, thus requiring a smaller energy input. The reason for this is that the train is propelled while coasting by the kinetic energy which has been stored in it, so that at the instant of applying the brakes the energy content is less than in run *A*. The most efficient run from the energy standpoint is therefore roughly that in which the train has coasted to the lowest speed at the time the brakes are applied.

Having determined the most efficient acceleration, this should be used for all runs made with the same motive power under similar conditions, irrespective of the length of the run. This may be done by making the different parts of the run proportional, as shown in Fig. 78.

By the same method as already used the speed–time curves for any length of run in any time may be determined. A series of such curves is given in Fig. 79, and is of value in the investigation of problems in train operation where the motive power is used only for acceleration.

Energy Consumption with Electric Motors.—We have already seen that the use of series electric motors causes a variation from the straight-line curves. The maximum acceleration is only continued up to a limited velocity; beyond that point the tractive effort falls off, and with it the acceleration becomes less. In determining the actual energy consumption the most exact method is to plot the current–time curve corresponding to the run, and from it obtain the power–time curve. From the latter the energy input to the motors can be found by summation. By continuing the process of plotting the power curves for the entire period of operation, and integrating them, the amount of energy necessary for the propulsion of the train may be determined. By adding the inputs for all the different trains on the system, the total energy consumption is found. In cases where the length of run and the character of profile do not vary widely, the process of integration may be shortened by selecting a type run, and deriving the total energy consumption from it. This is usually advisable only for preliminary estimates. For final calculations it is safer to take the actual load charts for determining the total energy required.

Effect of Gear Ratio on Energy Consumption.—It has already been shown that the gear reduction has a considerable effect on the load that a railway motor is forced to carry. Similarly, it is also a factor in affecting the energy consumption. We have seen

that, all other things being equal, the less the maximum speed, the smaller the energy input; so that the gear ratio which will give the lowest maximum speed and make the schedule should give the least energy consumption. A certain qualification of this statement must be made, in that if the gear reduction be too great, the maximum speed may be so low that no coasting can be included in the run if the schedule is to be maintained. This may actually increase the speed at which the brakes are applied, so that the energy which is ordinarily taken from the inertia of the train by coasting is all destroyed by the brakes. Such an extreme gear ratio is inadvisable, since some margin should be allowed to take care of heavy loads, low trolley potential, and other abnormal conditions of operation. If field control motors are used, as suggested in a previous paragraph, the gear ratio may be a maximum and still give a margin for taking care of special conditions.

Method of Comparing Energy Consumption.—In the comparison of equipments, or the same equipment under different operating conditions, it is useful to have some simple basis which may be used to facilitate computations. It is obviously impossible to make a complete set of graphical tests in each case, and yet it is important to have the comparison accurate. It is quite easy to place a watt-hour meter in the motor circuit, and get a record of the total energy input over an extended series of operations. This may then be compared directly with the energy for another run of the same length. The application of this method is quite limited, and it is virtually impossible to get consistent results.

A favorite method of comparing energy consumption is in the use of kilowatt-hours per car-mile, or per train mile. This gets away from the fundamental difficulty of the direct comparison, the variation in total distance, but it does not take into account the length of individual runs or the weight of the equipment. It is necessary to confine the application of this method to cars or trains of approximately the same weight, and even then the results may not be of great value.

Watt-Hours per Ton-Mile.—Since the energy for moving a given mass a specified distance should be the same with constant train resistance, the best method of comparing the energy consumption of different equipments is in terms of watt-hours per ton-mile. By this means the weight is eliminated, and cars or

trains of widely varying mass may have their energy consumption compared on a fairly rational basis. The effect of the length of run still remains; but the calculation very often is made to determine the influence of this variable, so that the method is directly useful in this connection.

To obtain the energy in watt-hours per ton-mile, it is only necessary to equip the car with a watt-hour meter to record the energy input, and supply some means of determining the average weight of the train and the total length of run. The result may then be reached directly. It is of great value in the comparison of different equipments in various kinds of service. While there is a wide range in the amount of energy required, the limits are fairly well defined for any particular class, so that the values obtained in different runs of the same kind may well be comparable.

Influence of Train Resistance on Energy Consumption.—A certain portion of the energy imparted to the train by the motors must always go to overcome train resistance. This amount is always equal to approximately twice the average resistance. Consider a train weighing T tons, moving at constant speed, V (miles per hour), the total train resistance being R (pounds per ton). The total output in kilowatts, P, is

$$P = \frac{VRT}{503} \tag{19}$$

The energy, W, in watt-hours per ton-mile, is

$$W = \frac{VR \times \text{hours run} \times 1000}{503 \times \text{miles run}} \tag{20}$$

Reducing this to terms of unity, it becomes

$$W = \frac{1000}{503} R = 1.99R \tag{21}$$

This equation holds under all conditions of operation, if the average value of train resistance, including that due to curves, be taken. This component of energy does not vary a great deal in individual runs, unless the speeds differ widely, or the car weights are so dissimilar as to be incomparable.

It is to be noted that this value of energy represents the motor *output* needed to keep the train in motion at constant speed, without stops. This condition is approached very nearly in long-distance runs, and gives the absolute minimum energy consumption for any form of normal operation. For example, a train consist-

ing of a single 50-ton car, running at a constant speed of 30 miles per hr., has a normal train resistance of approximately 12.5 lb. per ton. The output in watt-hours per ton-mile is then about 25. This value would also correspond to a 60-ton car at 35 miles per hr., or a 30-ton car at 20 miles per hr. The corresponding input to the train depends on the efficiency of the motors and control. If the average efficiency is 85 per cent. the input will be 29.4 watt-hours per ton-mile for this particular case.

Effect of Length of Run on Energy.—If it is necessary to limit the length of run, as is required in all practical operation, additional energy must be supplied beside that for overcoming train resistance. The amount expended in accelerating a train can be found at once, since it is stored in the kinetic energy of the train, and is numerically equal to $\frac{1}{2}Mv^2$, in foot-pounds. If the 50-ton car referred to in the preceding paragraph is brought up to a speed of 60 miles per hr., the energy imparted to it is

$$\frac{1}{2} \times \frac{50 \times 2000}{32.2} \times (60 \times 1.467)^2$$

$$= 12{,}000{,}000 \text{ ft.-lb.}$$

$$= 12{,}000{,}000 \times 0.0003766 = 4520 \text{ watt-hr.}$$

This represents the stored energy, which must be imparted to the train, neglecting the energy of the rotating parts. With the ordinary types of direct-current control the efficiency of the electrical equipment will not be more than about 55 per cent. during the acceleration period, so that the input to the car is

$$\frac{4520}{0.55} = 8230 \text{ watt-hr.}$$

The efficiency of the generating and substation equipment, and of the transmission and contact lines, during the period of heavy load while accelerating, will not be over 82 per cent., so that the total electrical input represented is approximately 10,000 watt-hr. at the switchboard. At the lowest cost of energy, 0.5 ct. per kw.-hr., this will amount to 5 cts., which is about the cost for stopping a limited interurban car. In sparsely settled territory, where a train may be required to make two separate stops for a single passenger, a 10-ct. fare will just pay for the cost of stopping the train.

A portion of the kinetic energy may be recovered if the train is allowed to coast before the brakes are applied in making a stop. In this way the energy may be returned in overcoming train resistance. It must be remembered that one-half the total kinetic energy will have been removed when the train has had its speed reduced to 0.7 of the maximum. For instance, the train in the last example will have given up 6,000,000 ft.-lb. if it has been allowed to coast down to a speed of 42 miles per hr.

The effect of stops on the energy consumption per ton-mile can be determined if the number of stops per mile is known. If the 50-ton car is running on a schedule which calls for one stop per mile,[1] the total energy will be that for train resistance already found, plus that for acceleration. This latter would be

$$\frac{12{,}000{,}000}{50} \doteq 240{,}000 \text{ ft.-lb. per ton-mile, or}$$

$$\frac{4520}{50} = 90 \text{ watt-hr. per ton-mile.}$$

The total *output* of the motors for such a run is therefore 90 + 25 = 115 watt-hr. per ton-mile. If the same maximum speed is attained, and the length of run is 5 miles, the total *output* of the motors is 18 + 25 = 43 watt-hr. per ton-mile. The corresponding *inputs* may be determined if the efficiency of the equipment is known. Assuming the same values for efficiency as before, the inputs to the car would be 193.4 and 62.1 watt-hr. per ton-mile, respectively, for the 1-mile and the 5-mile runs. The effect of frequent stops is thus seen to increase the energy by a marked amount when the maximum speed is high. For this reason the speed attained should be held to as low a value as possible, consistent with the required schedule speed. This may be done by the use of high acceleration and retardation. It is especially important on city lines, where the stops will average from four to ten per mile. High-speed operation under such conditions calls for an energy consumption out of all proportion to the value of the service rendered.

Another effect of stops is to increase the running time, or, conversely, to reduce the schedule speed. With ordinary interurban cars, and the usual schedule speed, rates of acceleration and braking, the effect of a single stop is to add about one minute to the running time. This is in addition to the time actually

[1] Such a schedule is manifestly impossible, but the value of the comparison is not changed thereby.

consumed in the stop, which may vary from a few seconds to several minutes.

It will be noted that the maximum speed attained, rather than the schedule speed, has an effect on energy consumption. If, by means of rapid acceleration and braking, the maximum is maintained for a large portion of the run, the schedule speed will be raised without a great increase in energy consumption. This is very marked in the shorter runs, and less so in the long ones. This is another argument for high rates of acceleration in city service. Since the schedule speed more nearly approaches the maximum, the greater the acceleration and retardation, the maximum speed required to give a certain schedule speed may be reduced; and the energy input is lowered in proportion to the square of the maximum speed.

Influence of Grades on Energy.—Since, in a complete round trip, a car must go up and down all the grades on the line, the net effect of them on the energy consumption is nil, if the brakes do not have to be applied to keep the train from reaching too high a speed. As many grades do require brake applications to prevent the attainment of dangerous velocities, there will be, in general, some increase of energy consumption if the grades are at all steep. The exact value can only be determined by an analysis of any particular problem.

In trunk line work, especially with heavy freight trains, the energy consumption will be increased to a marked degree if numerous grades are encountered. In the operation of freight trains, the maximum speeds are comparatively low, and the train resistance much less than in passenger service. On account of the large mass of freight trains, a large force is required for overcoming an opposing grade; and, to ensure safe operation, braking must be resorted to even on comparatively slight declines.

There is one case where the grades can actually be used to advantage in the propulsion of trains. If a down grade exists out of a station, the force of the grade will aid the motive power in accelerating the train; and, for trains coming into the station in the opposite direction, the same grade will help retard them. Such a grade is a positive benefit, provided all trains are required to stop at this point. If each main station can be located at the crest of a hill, the assistance of the grade can be had in both directions, and may even result in reducing the size of the

motive power required. For through trains, which do not stop at the stations, the only result is to add a certain amount of rise-and-fall to the line, which will have a relatively small effect in train operation.

In general, it is not possible to place all stations so as to make use of this phenomenon. In the case of elevated track through cities it can be done without any greatly increased expense. In elevated or underground railroads, the construction of the line with such grades is entirely feasible; and some roads have been built with the stations elevated above the general contour of the road.

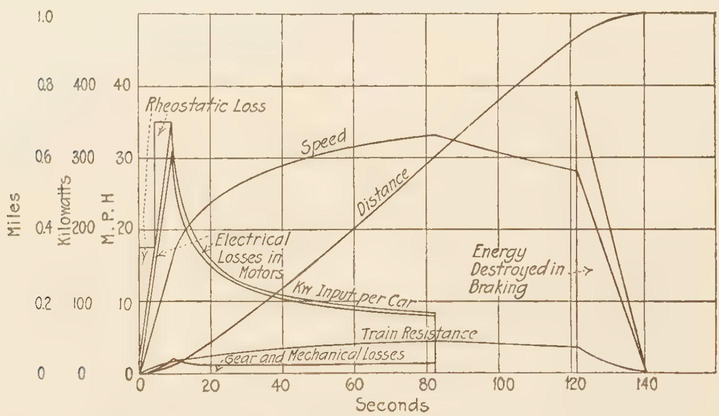


FIG. 80.—Distribution of energy consumption.

Showing the distribution of the energy input to a 50-ton car when making a 1-mile run. The sum of all the losses is just equal to the total energy input to the car.

Distribution of Energy Input.—After having taken up in detail the elements of the energy needed for train propulsion, it is interesting to see the distribution of the input. In Fig. 80 is shown the distribution of the energy for propelling a certain car over a run. Of the total amount supplied from the distributing circuit, a portion is lost in the wiring. During the operation of the controller, some of the energy is converted into heat in the resistance. Of the motor input, a portion supplies the electrical losses, and another part the mechanical losses in gears and bearings. The remainder is used for the propulsion of the train. Of this output, a certain amount is used to overcome train resistance, the balance being converted into kinetic energy, which is partly used to supply the train resistance while

coasting, the residue being absorbed in the brakes. The relations of the different uses of the input are clearly shown in the diagram.

Energy for Auxiliaries.—In addition to the energy used directly in the propulsion of trains, there is in most cases a demand for an additional amount in auxiliary circuits on the train.

Practically all electric cars, except the smallest single-truck city cars, are equipped with air brakes, the air being compressed by a pump on each motor car, driven by an electric motor. The requirements of this circuit, while small, must be added to the power demands; and, since the pump runs a considerable portion of the time, the amount of energy is worth taking into account. Tests[1] have shown that the energy for operating the air brakes in city service is from 1 per cent. to 2 per cent. of that required for the traction motors. In interurban service the energy for braking is from 5 to 12 watt-hr. per stop for a 40-ton car, depending on the rate of retardation. It is worth noting that on cars provided with air whistles, the energy used in this service is about equal to that for braking, unless special care is taken to prevent excessive use of the whistle. This has the effect of overloading the compressor. In cars equipped with electropneumatic control, there is additional compressed air needed. The amount for this is so small as to be of little consequence. On many rapid-transit lines, door-operating mechanisms are worked with compressed air. This makes a considerable addition to the other uses, and must be allowed for. Other pneumatically operated devices have been introduced which call for additional energy, so that the total required for these auxiliaries may amount to several per cent. of the total.

Practically all electric cars are lighted from the trolley circuit. The demand for energy can be readily calculated. Although it is not large for a single car, it makes a considerable total for a city system. The older forms of lighting almost invariably consist of 16-c.p. carbon lamps, consuming approximately 55 watts, and connected in series of five on the trolley circuit. The number of lamps per car varies from five to twenty-five, depending on the size of the car and the individual taste of the designer. In more recent equipments tungsten lamps have been used to advantage to reduce the energy consumption, cutting it down in

[1] *Report of the Electric Railway Test Commission*, McGraw Publishing Co., 1906.

extreme cases from 1.5 kw. to 0.5 kw., and at the same time giving better lighting.

Heating of city cars is most frequently done with electric power. The amount of energy required to keep the temperature to a reasonable point on cold days is quite considerable, a test on a large city road[1] showing a power consumption of 3.3 kw. at full load on the heaters, or 16 per cent. of the total power taken by the car. In elevated service, under similar conditions, the power for heating was 8.25 kw. or 18 per cent. of the total.

For high-speed interurban roads the demands for heating are much greater, so that in many cases heaters taking energy direct from coal are used on account of their lower operating cost. This is discussed more fully in Chapter VIII.

Regeneration of Electric Energy.—It has been shown that of the total input for train operation, a large portion is used to produce kinetic energy. In case grades are encountered, another portion of the input will be converted into potential energy. While these forms readily admit of reconversion into some other, they are, in general, not utilized, since it is necessary to destroy the energy of the train by means of brakes in order to prevent too high a speed, or to bring the train to rest. If this energy could be recovered in some useful form, the total requirement would be that needed to overcome train resistance alone, with an addition for the inevitable losses in the electric circuit.

Many attempts have been made to recover an appreciable amount of this energy and return it to the electric circuit. Generally speaking, all of the proposed methods include the use of the motors as electric generators. To get a motor which will deliver energy to the line requires that the magnetic flux be to a large extent independent of the load. In direct-current practice, a motor with shunt characteristics is necessary, and in alternating-current service a shunt characteristic must be obtained, or the motor must be of the induction type. None of the motors which have been most successful in railway service (*i.e.*, series motors) lend themselves readily to the generation of current. A glance at the curves of a series railway motor (see Fig. 19) shows that a current will be taken, no matter how high a speed is reached. This is true whether the series motor is operated on direct current or on alternating current. The shunt motor is, however, well

[1] Herrick and Boynton, "American Electric Railway Practice," McGraw-Hill Book Co., Inc., 1907.

adapted for this service. In Fig. 81 the curves of the shunt motor have been extended beyond the origin to show the characteristic performance under a wide range of conditions. If the speed of the motor is increased beyond the normal no-load speed, the current in the armature will reverse, and the machine will become a generator, returning current to the distributing circuit. If the railway system is at all extensive, the current thus fed back into the line can be used for the propulsion of other cars, and will reduce the load on the generating station. The proper condition for feeding back into the line is reached whenever the motor speed exceeds the no-load speed. In other words, when the train is

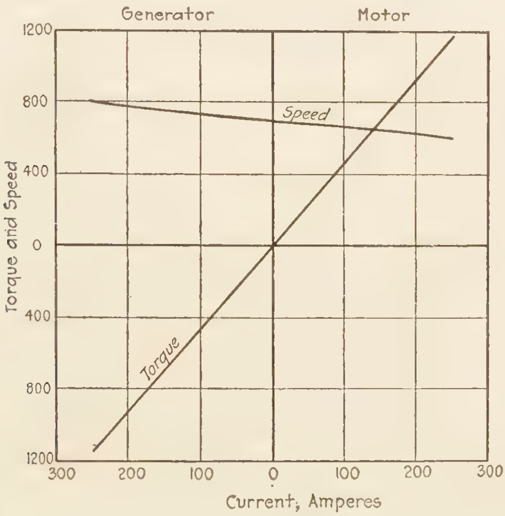


FIG. 81.—Shunt motor characteristics.

The performance curves of the shunt motor, Fig. 15, are re-drawn to show the performance when the speed exceeds the normal no-load speed of the machine.

going down a hill on which the tractive effort due to the grade is greater than the train resistance, the armature current will reverse without any change in the motor connections. Regeneration is thus entirely automatic.

With the induction motor, the performance is almost precisely the same as with the direct-current shunt motor. In neither case, however, is the motor inherently suited to give the large tractive effort required for starting with a high acceleration. For this reason motors of the constant-speed type have never become

popular for traction. In a hilly country, however, the value of the energy saved may overbalance the disadvantages.

When motors of the series type are to be employed for regeneration, it is necessary to modify their characteristics by the addition of a shunt winding, or by a reconnection of the series fields to the line, as in Fig. 82. This gives them performance curves like those shown in Fig. 81, and the operation is the same as that of the shunt machine. In this case it is necessary to provide proper controller connections for making the desired changes as needed. For small equipments the complication introduced in the control, and the addition of an extra winding, have prevented the adoption of this feature.

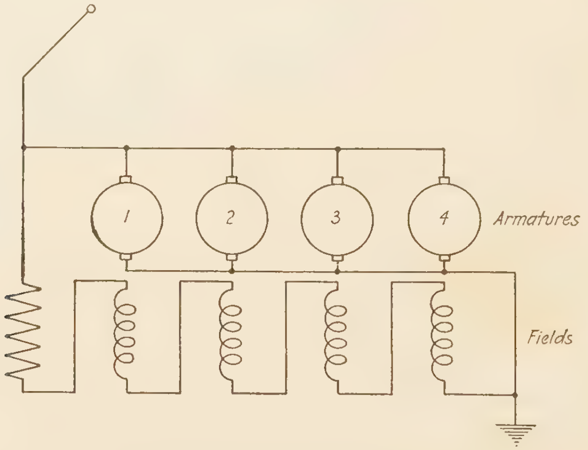


Fig. 82.—Arrangement of series motors for regeneration.

The fields are placed in series with a suitable resistance, while the armatures are connected in parallel across the line.

In order to return a portion of the energy of acceleration, it is further necessary to change the characteristics of the motor in such a manner that it will generate in spite of a reduction in speed. In the shunt machine, this may be done if the field strength be made considerably greater. By increasing the flux the normal speed is reduced, so that if this change is suddenly made the motor will then be operating above its new no-load speed, and energy will be returned until the speed corresponding to the particular field strength has been reached. The range through which this can be accomplished may be further increased if two or more armatures are put in series as the train speed becomes less. With

induction motors the same result can be had by concatenation, or by changing the number of poles. The range of speed over which energy can be regenerated is of course limited in any type of motor; but it must be remembered that the larger part of the energy can be returned by a comparatively small speed reduction. For instance, if induction motors are employed, and the speed is reduced to one-half by concatenation, the amount of energy returned is three-fourths of the total kinetic energy at full speed.

It must not be taken for granted that the entire amount of stored energy can be returned to the electric system and used at some other point. The inevitable losses in the machines and in the electric circuits will reduce the quantity available by a considerable degree. The net amount of energy which can be returned may be quite large in certain classes of service. On mountain roads, for instance, where braking is ordinarily used to prevent an excessive speed, the energy which can be recovered may amount to a material proportion of the entire demand. In such a case the necessary complication of the motors and control may be well worth while.

Effects of Regeneration on Equipment.—The use of the traction motors for the return of energy to the line cannot be done without a definite increase in the heating. The motors are working for a larger portion of the total time, so that both the r.m.s. current and the average motor potential are higher; this results in greater copper and iron losses, with increase in the average motor load. If the motors are only of sufficient continuous capacity to propel the cars in the usual manner, the addition of the regeneration feature will cause them to be loaded beyond their normal rating, and hence to overheat.

In many cases the motors will have sufficient reserve capacity, so that the addition of regeneration will still keep the load within the rating of the motors, in which event no change is necessary. Each case must be considered separately, the values of r.m.s. current and average motor potential being determined by the method already given.

Another result of the regeneration of energy is the reduction in brake-shoe friction needed in controlling the speed of the train. Since in ordinary operation the energy of the train is absorbed by the brake shoes, with consequent production of heat, there will be a considerable amount of brake-shoe wear caused by the friction. The use of regeneration removes a large amount of

work from the brakes, so that the shoe wear is materially reduced, resulting in a saving of cost in brake shoes and wheels. The wheels are also subject to various troubles from overheating. In general, the wheels of American freight cars are of cast iron, with the treads chilled to resist wear. The alternate heating and cooling due to braking sometimes cause annealing of the chill, with resultant increased wear. In extreme cases the metal is likely to crack or "shell out," necessitating the removal of the affected wheel from service, perhaps long before it has reached the normal limit of life. A large portion of this wear can be prevented by regeneration, which will also relieve other parts of the equipment, such as the brake rigging, and will reduce the load on the air compressors and other parts of the braking system. Such advantages as these may be worth more than the actual return of energy.

A possibility exists in connection with the use of direct-current shunt motors for regeneration. If a shunt motor be made with a maximum strength of field at least equal to the greatest available field on a series motor of the same rating, it will give equal or greater torque with the same armature current. It can accelerate up to the normal operating speed, which will be approximately the same as that of the series motor at maximum current. For acceleration above this point, the strength of field can be reduced by the insertion of resistance in series with the shunt field winding. Proper proportioning of the resistance will allow the motor to produce an acceleration curve approximately the same as that for a series motor of equal capacity. A motor of this type will have the advantage over the series motor that any speed above that with the maximum field strength is an operating one; and all the operating speeds will give practically maximum efficiency. The same motor can be used for slow-speed work, with rapid acceleration, on city streets, or for high-speed work on private right-of-way. Regeneration on down grades can be accomplished at any desired operating speed by proper adjustment of the field resistance. To return energy to the line when stopping, the field strength can be increased by cutting out resistance, thus increasing the counter e.m.f. of the motor until energy is recovered. The motor armatures can be connected in series to carry the regeneration still further.

The principal objection to this type of motor and control appears to be the lack of safeguard against overload. With

the series machine, an increase in load is accompanied by correspondingly greater field strength, thus automatically reducing the speed and limiting the overload. With the shunt motor no such inherent safety device is present, the field strength remaining constant unless varied independently. It is possible, however, to introduce a relay which will automatically increase the field current when an overload occurs, thus giving the same form of protection as in the series motor. Although this method of operation has never been tried, it has very attractive possibilities, and may in the future be extensively used, both for interurban and trunk-line service.

CHAPTER VII

BRAKING OF ELECTRIC RAILWAY TRAINS

Importance.—Even though it is of importance to get a train in motion rapidly, it is none the less essential to be able to arrest its movement when desired, at a rate comparable with the acceleration, and in such a manner that the action may be predetermined with a considerable degree of accuracy. Indeed, from the standpoint of safety, the braking of trains is of even greater importance than their acceleration.

It is shown in the previous chapter that a high rate of acceleration is required to reduce the amount of energy consumed. It is equally true that a rapid retardation is desirable to cut down the running time between stops. It must be noted, however, that one of the economies effected by the rapid retardation is due to the fact that the train is able to propel itself for a portion of the distance by its own momentum, for the rapid reduction of speed produced in braking by ordinary methods converts a large portion of the stored energy into heat without performing any useful work. Granted that the most efficient run is the one where the brakes are applied at the lowest practicable speed, the retardation from this point should be the highest allowable, since the added distance covered when a lower rate of braking is used is more than offset by the decreased average speed at which this part of the run is made.

Methods Available for Retardation.—Since it is universally granted that some form of braking, by means of which the speed of a train may be reduced at a rapid rate, is a necessity, the next thing is to determine what forces may be employed to effect this retardation, and what methods may be used to make them available.

One force is always present, and is universally applicable in decreasing the velocity. This is the train resistance. Since it increases with the speed, it is greatest when it is most needed. If curvature of the track is present, it will also aid in retardation. Grades may assist, or may hinder, depending on the direction of

motion. The train resistance, even in favorable cases, is not sufficient to control the train motion satisfactorily. The force due to this, acting on a single 50-ton car at a speed of 60 miles per hr., is about 27 lb. per ton, which will produce a retardation of approximately 0.27 miles per hr. per sec., which is entirely inadequate for practical operation, since, if the force remained the same until the train were brought to rest, a time of 221 seconds would be necessary to stop the car. It is evident that some additional force is required.

The most obvious method of obtaining an additional retarding force is to produce friction against the track. This has been used in some cases. On a few gravity roads dogs are employed which engage the ties, so that if the car stops on the up-grade, the dogs will act and prevent the car from running backward down the track. A more refined method of producing friction against the track is to use metallic blocks which may be pressed on the rails. This has been employed in connection with certain of the cable roads which were popular at one time. This method of retardation is poor, since, as will be seen, the sliding friction obtainable between the brake blocks and the rails is less than that which can be obtained by other means.

The other available method of utilizing friction as a retarding force is to produce the friction by the pressure of blocks against the car wheels. When this is done, it is essential that the wheels have sufficient adhesion on the rails to prevent sliding, or the conditions would be the same as with the track brake already described; and the rubbing of a single place on a wheel against the rail would result in wearing a flat spot on the locked wheel, which would hinder its further operation.

The first railway cars were readily brought to rest by means of force applied to wooden blocks bearing against the wheels. This natural solution of the problem needed modification for heavier equipment only by increasing the pressure of the brake shoes, and the use of a material which would resist wear while giving sufficient friction to be effective. The force was applied to the shoes by means of a system of levers operated by hand. This type of brake has been used to a very great extent for all classes of vehicles. It was the only kind employed on steam railway cars for many years, and is today retained as a valued auxiliary.

Need for Power Brakes.—Although the hand brake, as just described, was adequate for the light cars and low speeds in com-

mon use 25 years ago, its limitations have been exceeded in nearly every form of railway vehicle. Except in the case of slow-speed city cars of light weight, some form of brake applied by a power more certain and of greater amount than the available muscular force of the operator, must be employed. It should be remembered that a large share of the kinetic energy of the moving train must be absorbed by the brakes, only a small portion of it being taken care of by the train resistance. Since the kinetic energy increases directly as the weight and as the square of the speed, it may be seen that the stopping of a 20-ton car from a speed of 20 miles per hr. will require the absorption of eight times the energy possessed by a 10-ton car running at 10 miles per hr. While the hand brake will take care of the latter case with ease, the former is practically beyond its range of efficient operation. As 20 tons is about the minimum weight of car now in use, except for very light city service, the application of power brakes to all electric cars has been agitated in many quarters. A study of the different forms of power brakes available is therefore pertinent.

Nature of Braking Phenomena.—All the mechanical relations in braking follow the laws of motion. These laws have already been discussed in some detail in Chapter II. Retardation is a phenomenon of a character precisely similar to acceleration, and may be correctly regarded as negative acceleration. It will not be necessary to repeat the fundamental relations; but it is well to note that, retardation being opposed to the direction of motion, the algebraic signs of the functions should be carefully checked in order to prevent mistakes.

Adhesion Coefficient.—It has already been mentioned that, in order to utilize friction between the wheels of a train and brake shoes bearing against them, the force applied shall not be so great that the available adhesion between the wheels and the rail shall be exceeded. The coefficient of sliding friction is less than that of rolling friction (or adhesion). If sliding takes place the maximum braking effort which can be obtained will be reduced. It has also been pointed out that sliding causes undue wear on the wheels.

Although the values of adhesion have never been experimentally checked through a wide range of conditions, the following fairly represent the result of such tests as have been made:

COEFFICIENTS OF ADHESION BETWEEN DRIVERS AND RAIL[1]

	Normal	With sand
Most favorable condition	0.35	0.40
Clean dry rail	0.28	0.30
Thoroughly wet rail	0.18	0.24
"Greasy" moist rail	0.15	0.25
Sleet-covered rail	0.15	0.20
Dry-snow-covered rail	0.11	0.15

It may be noted from the above table that the normal adhesion with dry rails is over 25 per cent.; while with the use of sand the coefficient need not fall below 20 per cent. except with the most unfavorable conditions. In general, a maximum force equal to about one-quarter the train weight may be applied at the wheel treads either for acceleration or retardation, without slipping. If all of this force were availed of it would produce an acceleration amounting to

$$2000 \times 0.25 \times 0.01 = 5 \text{ miles per hr. per sec.}$$

This includes energy of rotation equivalent to one-tenth of the linear inertia. This extreme value of acceleration is seldom reached in practice, since it is in most cases far beyond the maximum capacity of ordinary motive powers or brake rigging. On account of the variable character of the adhesion coefficient, it would be unwise to attempt to design braking equipment up to this limit. In most cases, accelerations and retardations of from 1.5 to 2.0 miles per hr. per sec. will be found ample for service conditions, although greater rates are demanded for emergency braking.

It may be noted in this connection that the adhesion is affected to a considerable extent by the area of the contiguous surfaces. It is usually assumed that the contact between wheel and rail is a line; but, since both are compressed to some extent, the contact really is a surface. The shape of this surface varies with the elasticity of the metal, and is evidently greater with large diameter wheels than with small ones. The reduction in adhesion is very marked in locomotive testing plants, where the drivers are carried directly on supporting wheels of approximately the

[1] EDW. P. BURCH, "Electric Traction for Railway Trains," p. 406, McGraw-Hill Book Co., Inc., 1911.

same size. In this case slipping occurs with much lower values of adhesion than on ordinary track.

Sliding Friction.—This follows a quite different set of laws from rolling friction. It was first given a thorough investigation by George Westinghouse and Sir Douglas Galton in a series of tests made on the London, Brighton and South Coast Railway (England) in 1878, and reported by Galton to the (British) Institution of Mechanical Engineers in April, 1879. These tests, known as the "Galton-Westinghouse tests," have become classic, and summarize practically all that is known at the present time

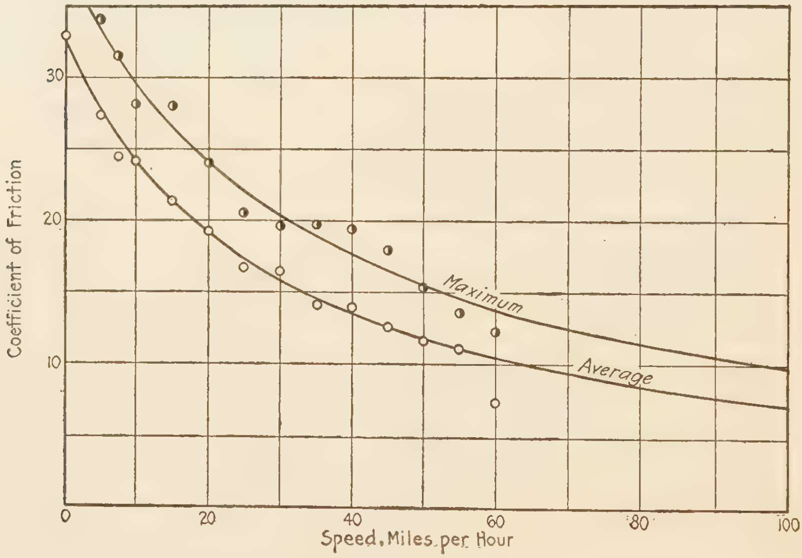


FIG. 83.—Variation in friction with speed.

on the subject of sliding friction. They were made on cast-iron brake shoes bearing on steel-tired wheels, and cover a wide range of conditions. The best published interpretation of these tests is that made by Mr. R. A. Parke in a paper presented before the American Institute of Electrical Engineers.[1] He finds that the *average* coefficients of friction for different speeds may be expressed by the equation

$$f = \frac{0.326}{1 + 0.03532V} \tag{1}$$

[1] R. A. PARKE, Railroad Car Braking, *Transactions* A I. E. E., Vol. XX, p. 235.

where V is the speed in miles per hour, and f the coefficient of sliding friction. For *maximum* observed coefficients, the equation is

$$f = \frac{0.382}{1 + 0.02933V} \tag{2}$$

The graphs of these equations are shown in Fig. 83. The points plotted are the values obtained in the Westinghouse tests. It may be clearly seen that the coefficient of friction falls rapidly from a maximum of 0.33 at standstill to less than 0.11 at a speed of 60 miles per hr.[1] If a braking system were designed to utilize the total adhesion at standstill, the same pressures would give only one-third the value determined in the preceding paragraph. For any other value of braking effort a corresponding reduction in friction with speed will take place.

Effect of Distance on Sliding Friction.—Further experiments made by Captain Galton appear to show that the coefficient of friction also decreases as a function of the time during which the rubbing of two surfaces continues. The results of these tests have been interpreted by Mr. Parke to indicate that there is a different curve corresponding to each initial coefficient of friction, and that these curves are of the form

$$f_1 = \frac{1 + hs}{1 + cs} f \tag{3}$$

where f is the initial coefficient of friction, corresponding to a particular speed and pressure, s is the distance, in feet, traveled while the rubbing surfaces are in contact, f_1 the coefficient of friction after any elapsed distance, and h and c are constants. Using the results of the Galton tests, the values found for h and c cause equation (3) to become

$$f_1 = \frac{1 + 0.000472\,s}{1 + 0.002390\,s} f \tag{4}$$

The graphs of this equation, for various initial speeds and coefficients of friction, are shown in Fig. 84. The points are those found by Captain Galton at the corresponding speeds as designated by the figures. Later experiments would indicate that a constant friction is reached much sooner than would be derived

[1] More recent tests made by the Pennsylvania Railroad agree in general with the curve of maximum values, but sufficient points were not obtained to determine accurately its form.

by the above equation, and that a value considerably greater than that found above is correct. The reason why Galton's results are low may be because of the short distances included in the tests; none of them was for a greater recorded length than 900 ft. The points on the curve in which the coefficient is rapidly falling therefore preponderate.

It is unfortunate that no completer mathematical utilization of the characteristic reduction of friction with time can be made. Although it exerts a marked influence on the amount of time needed for bringing a train to a stop, the variation of conditions affects the decrease to such an extent that no exact rules can be formulated. Since the grade directly adds to, or subtracts from, the braking force applied, it must change the rate of retarda-

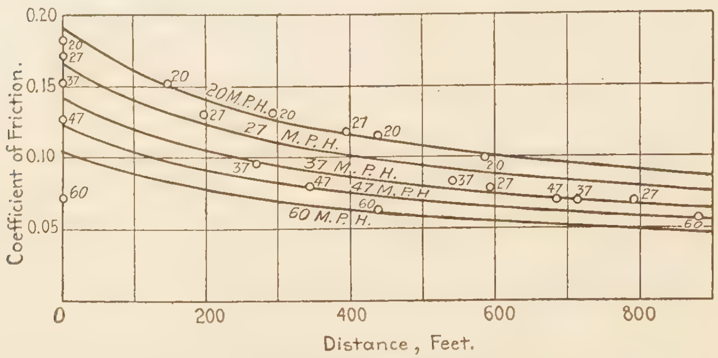


FIG. 84.—Variation of friction with distance.
The small numbers beside the points refer to the speeds at which the tests were made.

tion, independently of the coefficient of friction. This has the effect of varying the time of rubbing between shoe and wheel corresponding to a given braking force, so that the final result is to change the relation of the coefficient of friction and time or distance. The indication is that the brakes are relatively more efficient on an up grade, and less so on a down grade.

The relation between the coefficient of friction and the braking pressure is quite complicated, but tests indicate that the coefficient varies inversely with it.

The bad results of sliding the wheels, as increasing the time or distance needed to bring a train to a stop may be seen by a comparison of the values of rolling friction (adhesion) and sliding friction. When the wheels keep their grip on the track,

and rotate, the maximum braking force that can be applied is that which produces a frictional resistance just below the total adhesion of the wheel on the rail. By the use of sand, this can nearly always be kept over a value of 0.2. When the braking force exceeds the limiting value of adhesion, the resistance at the contact of wheel and rail obeys the laws of sliding friction; and it may be seen that even for moderate speeds the retarding force will be less. For example, the coefficient of sliding friction at a speed of 20 miles per hr. is 0.192, which is less than the adhesion mentioned above; and, since the friction becomes less with the distance of application, this represents a maximum value at that speed.

Combined Effect of Variations in Friction Coefficient.—In determining the retardation which will be produced by the application of a given braking force, all of the variables which enter must be taken into account. The initial friction which is obtained at any given speed can be found with considerable accuracy. It apparently declines for a certain distance, due to the effect of the general reduction in friction with time of application; but, since the braking force is simultaneously lowering the speed, the friction has a tendency to become greater. As the train moves forward, the increase of friction with the lower speed will overbalance the reduction due to the time the brakes have been applied, first very slowly, and then more rapidly, until, when the speed is very low, the friction becomes so great as to stop the train abruptly. This effect on passenger car braking can be noticed at any time. To offset this final increase in friction, it is customary to reduce the braking force as the train nears a stop.

Determination of Correct Retardation.—In connection with the energy consumption of electric trains, it has been seen that in general the most economical run is that in which the acceleration is the highest. A great deal of careful experimental and theoretical engineering has been done to determine how high the acceleration may be carried; and the values in use today represent the maxima that can be applied for various classes of service. On the other hand, very little has been accomplished in the employment of high braking rates in practice. Although brakes are usually designed to give a very high retardation for emergency service, the regular applications use lower values than those of the corresponding accelerations. This is the more

marked, since the use of a large tractive effort calls for a great expenditure of energy during the whole starting period, while a high braking force merely takes a larger volume of compressed air, furnished at a cost very much less than that of the energy for starting. In other words, it should be profitable to use regularly for service stops, braking rates which are as high or higher than the corresponding accelerations, working the braking apparatus on the edge of the emergency application for each stop. This will also eliminate the personal element to some extent, and allow the predetermination of train performance with greater accuracy.

Transmission of Braking Forces.—In the use of the friction between wheels and brake shoes for the production of the retarding force in train braking, it is necessary to have an adequate means of transmission of the force to the desired points, and to be able to control it in amount. Since it is undesirable to slide the wheels, precautions must be taken to prevent this in any brake application, while at the same time the force used is as near the allowable limit as needed for adequate braking. To determine what this maximum force can be requires a knowledge of the distribution of the weight of the car on its supporting wheels. It might be assumed that the weight is carried uniformly on all the wheels; but, due to the moment developed by the application of the retarding force away from the center of gravity of the car, the distribution will be considerably different from this average value.

Since the adhesion between wheel and rail is ultimately used as the basis of ordinary braking systems, the point of application of the force is about as far removed from the theoretically correct position as possible. If the car is of the single-truck type, it can be considered as a single moving mass; or if of the double-truck type, of three distinct masses, the car body and the two trucks.

Distribution of Forces on the Car.—Since the center of gravity is above the point of application of the braking force, there is a tendency to rotate the car body in the same direction as that of the wheels. This rotation is prevented by the production of a greater supporting force at the front end (either the forward truck, in a double-truck car, or the forward wheels in a single-truck car) sufficient to balance the turning moment. It is evident that the total pressure of all the wheels on the track must

be equal to the total weight carried, so that the effect of rotation of the car body and trucks is the same as though a portion of the mass were actually transferred from the rear to the forward wheels or truck. The pressure of the forward wheels of the leading truck will be the greatest, and that of the rear wheels of the rear truck the least. Since most cars must be ready to operate in either direction with equal facility, the pressure of the brake shoes must not exceed that which will skid the wheels on the rear axle of the car. In ordinary passenger cars, with maximum rates of retardation, the pressure on the rail, for the rear pair of wheels, is less than 85 per cent. of the normal pressure at standstill or at constant speed. This represents the limit of the braking force that can be applied, and it must be seen that it causes a considerable reduction from the maximum

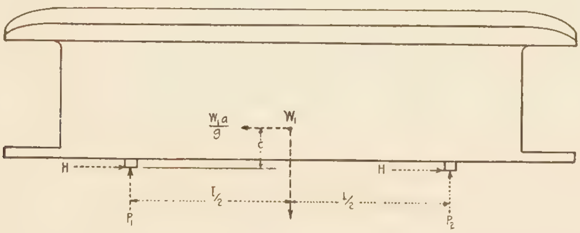


Fig. 85.—Distribution of braking forces on car body.

braking effort theoretically possible were the forces properly adapted to the individual wheel loads.

In order to determine the actual forces, it is necessary to consider the reactions existing between the car body and the trucks, and also those in the trucks themselves. In this way it is possible to compute the allowable braking forces for any set of conditions.[1]

The body of a car, shown in Fig. 85, is considered as a "free body," the trucks having been replaced by their reactions P_1 and P_2. The trucks being alike and the braking forces on each wheel being the same, the horizontal effort of the retarding force will be the same for each truck, being represented by H. The car weight, W_1, acts vertically downward at its center of gravity, which is, in ordinary cases, at a distance $\frac{l}{2}$, or midway between the two supporting trucks. The action of the brakes causes the car

[1] The following treatment is based on the method of R. A. Parke, Railroad Car Braking, *Transactions* A. I. E. E., Vol. XX, p. 252 (1902).

as a whole to be retarded at a rate a, so that the total retarding force is

$$\frac{W_1a}{g} = 2H \tag{1}$$

or

$$H = \frac{W_1a}{2g} \tag{2}$$

Also, since the total reaction of the trucks must evidently be equal to the entire weight of the car,

$$P_1 + P_2 - W_1 = 0 \tag{3}$$

Taking moments about P_1 we have

$$W_1\frac{l}{2} - P_2l = \frac{W_1ac}{g} \tag{4}$$

whence

$$P_2 = \frac{W_1}{2} - \frac{W_1ac}{gl} \tag{5}$$

Substituting the value of P_2 in equation (3),

$$P_1 = \frac{W_1}{2} + \frac{W_1ac}{gl} \tag{6}$$

A comparison of equations (5) and (6) shows that the normal weight $\frac{W_1}{2}$, supported by each truck, has been changed by the removal of an amount $\frac{W_1ac}{gl}$ from the rear and its transfer to the forward truck.

If the car is intended for operation in both directions, as is usually the case, the determining factor is the pressure allowable on the rear truck, and a consideration of that will be equally applicable to the other when the motion is reversed. For cars designed to run in one direction only, it is possible to modify the braking forces to apply a greater pressure to the shoes on the forward truck. In that case a similar calculation to the one following can be made for the forward truck, the relations being identical.

Distribution of Forces on the Truck.—Considering the rear truck as a free body, Fig. 86, the car has been replaced by its pressure P_2, the track by the reactions R_1 and R_2, and the braking force on the rails by the reactions T_1 and T_2. Since each pair

of wheels must rotate as a single unit, being rigidly pressed on the same axle, the forces T_1 and T_2 may be considered as combined for their respective *pairs* of wheels. The truck weight W_2 acts through the center of gravity of the truck, at a distance d above the rail and midway between the wheels.

Taking a summation of the vertical forces, we have

$$R_1 + R_2 - W_2 - P_2 = 0 \tag{7}$$

and a summation of the horizontal forces gives

$$T_1 + T_2 - H - \frac{W_2 a}{g} = 0 \tag{8}$$

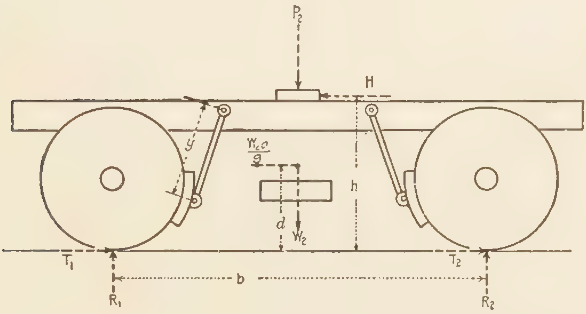


FIG. 86.—Distribution of braking forces on truck.

Taking moments about R_1,

$$\frac{W_2\,b}{2} + \frac{P_2\,b}{2} - R_2 b - Hh - \frac{W_2 ad}{g} = 0 \tag{9}$$

or

$$R_2 = \frac{W_2}{2} + \frac{P_2}{2} - \frac{Hh}{b} - \frac{W_2 ad}{gb} \tag{10}$$

Substituting the value of R_2 in equation (7),

$$R_1 = \frac{W_2}{2} + \frac{P_2}{2} - \frac{Hh}{b} + \frac{W_2 ad}{gb} \tag{11}$$

Replacing H and P_2 by their values found in equations (2) and (5), equations (8), (10) and (11) become, respectively,

$$T_1 + T_2 = \frac{W_1 + 2W_2 a}{2g} \tag{12}$$

$$R_2 = \frac{W_1 + 2W_2}{4} - \frac{W_1 a}{2g}\left[\frac{h}{b} + \frac{c}{l}\right] - \frac{W_2 ad}{gb} \tag{13}$$

$$R_1 = \frac{W_1 + 2W_2}{4} + \frac{W_1 a}{2g}\left[\frac{h}{b} - \frac{c}{l}\right] + \frac{W_2 ad}{gb} \tag{14}$$

A comparison of equations (13) and (14) shows that the result of applying the brakes is to reduce the rail pressure on each pair of wheels of the rear truck by an amount $\frac{acW_1}{2gl}$ [equations (5) and (6)]; and has also transferred from the rear to the forward wheels of the truck an amount equal to

$$\frac{ahW_1}{2gb} + \frac{adW_2}{gb}$$

If the car is to be operated only in one direction, the values of all forces may be determined and all pressures on the brake shoes modified accordingly. Ordinarily cars must be suitable for operation in either direction; in which case the maximum pressure for any pair of wheels must be reduced from $\frac{W_1 + 2W_2}{4}$ to the value given in equation (13).

Solving equation (12) for a we have

$$a = 2g\,\frac{T_1 + T_2}{W_1 + 2W_2} \tag{15}$$

Since $W_1 + 2W_2$ is the total weight of the car the equations above may be simplified by designating by W the total weight, or

$$W = W_1 + 2W_2 \tag{16}$$

Equation (15) then becomes

$$a = 2g\,\frac{T_1 + T_2}{W} \tag{17}$$

The equations for the rail pressures R_1 and R_2 hold for any values of T_1 and T_2 that may exist. If the coefficient of adhesion be represented by f_1, then

$$T_1 = f_1 R_1 \tag{18}$$

and

$$T_2 = f_1 R_2 \tag{19}$$

We may now re-arrange the expressions for rail pressures, solving them for T_1 and T_2 from equations (18) and (19), and reducing by the substitution of values of W and a from equations (16) and (17). Then

$$T_1 = \frac{f_1 W}{4} \times \frac{Wb + 2f_1(W_1 h + 2W_2 d)}{(W + 2f_1 W_1 \frac{c}{l})b} \tag{20}$$

$$T_2 = \frac{f_1 W}{4} \times \frac{Wb - 2f_1(W_1 h + 2W_2 d)}{(W + 2f_1 W_1 \frac{c}{l})b} \tag{21}$$

Under normal conditions, with the direction of motion reversible, the greatest pressure that can be applied to any pair of wheels and will slide none of them may be determined by making

$$T_1 = T_2 = f_1 R_2 \tag{22}$$

Substituting this value in the equation for R_2, and simplifying

$$T_1 = T_2 = \frac{f_1 W}{4} \times \frac{Wb}{Wb + 2f_1[W_1(h + \frac{cb}{l}) + 2W_2 d]} \tag{23}$$

From the dimensions of standard passenger cars without electrical equipment, and assuming a coefficient of adhesion $f_1 = 0.25$, it is found that, instead of having a value of $\frac{f_1 W}{4}$ for each pair of wheels, the adhesion is only $0.834 \frac{f_1 W}{4}$. Another way of looking at this is that if the brake-shoe pressures are equal on all wheels, the available adhesion for obtaining retardation is only 83.4 per cent. of the total weight of the car. If these pressures can be adjusted to allow for this transfer of weight the effectiveness can be increased over 16 per cent.

Although it is not practical to properly alter the shoe pressures between the two trucks without changing the fixed leverages of the brake rigging, it is possible to make a readjustment of the forces acting on each to compensate for the weight transfer from the forward to the rear wheels of that truck.

In common practice, the brake shoes may bear on the wheels either on the inside or the outside of the truck frame. Ordinarily, they are placed on the inside, as shown in Fig. 87. When this arrangement is used, it is possible, by varying the angularity of the hanger link, to introduce a force which will equalize to any desired degree the transfer of weight from the rear to the forward axle.

In Fig. 87 are shown the forces acting on the truck during an application of the brakes. The forces P and P are those supplied

from the brake beam, and are really equally divided between the two wheels at opposite ends of an axle; while the other forces occur separately, but generally in equal amount, at the individual contact points. As mentioned before, it is simpler to treat the pair of wheels on a single axle as one unit. Opposed to the brake-shoe pressure are the reactions Q_1 and Q_2 from the wheels, and the frictional forces F_1 and F_2 result from these. The reactions on the brake shoes from the hanger links are represented by V_1 and V_2. The middle of the brake shoes is usually located a small distance below the center of the wheels; the angle between the direction of Q_1 and Q_2 and the horizontal, is represented by θ (by similar triangles). The mean values of the frictional

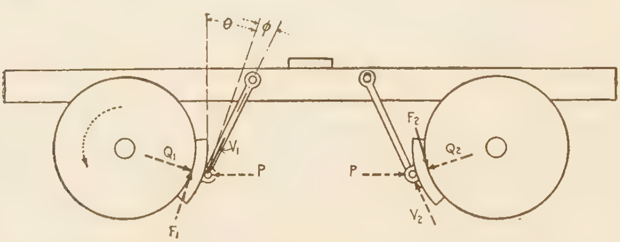


Fig. 87.—Equalization of brake-shoe pressure.

By properly offsetting the brake hangers, the weight transfer between the wheels of the truck may be compensated, allowing a greater total braking force.

forces F_1 and F_2 must therefore be inclined from the vertical at the same angle. In the particular example of brake rigging shown, the hanger links are inclined to the tangential direction of the friction by the angle ϕ. Resolving the forces into rectangular components, referred to the axes of the hanger links for each pair of wheels, we have

$$Q_1 \cos \phi - F_1 \sin \phi - P \cos (\theta + \phi) = 0 \tag{24}$$

$$Q_2 \cos \phi + F_2 \sin \phi - P \cos (\theta + \phi) = 0 \tag{25}$$

Now, designating the coefficient of brake-shoe friction by f_2,

$$F_1 = f_2 Q_1 \tag{26}$$

and

$$F_2 = f_2 Q_2 \tag{27}$$

Re-writing equations (24) and (25) with these values and solving for ϕ and P,

$$\tan \phi = \frac{1}{f_2} \frac{F_1 - F_2}{F_1 + F_2} \tag{28}$$

$$P = \frac{(F_1 + F_2) \cos \phi - f_2 (F_1 - F_2) \sin \phi}{2f_2 \cos (\theta + \phi)} \tag{29}$$

Effect of Rotational Inertia.—In addition to destroying the energy of translation existing in the moving car, the brake-shoe friction must also absorb the rotational energy of the wheels and axles, and in the case of motor cars or locomotives, of the motors. This inertia is entirely independent of that due to translation; and in destroying it the coefficient of adhesion between wheels and track does not enter. Practically, a greater braking force must be used to produce a given retardation when the rotation of the wheels and other parts is taken into consideration.[1]

Letting r represent the radius of the wheel, the retardation a of the car is also accompanied by a retardation $\frac{a}{r}$ in the motion of the wheel. Calling the weight of one wheel and one-half of its axle w_1, and the radius of gyration of this part about its axis k_1, the retarding force necessary to be applied at the wheel tread is

$$\frac{w_1 k_1^2 a}{gr^2}$$

for a truck without electrical equipment. For a motor truck this force must be increased by the amount

$$\frac{w_2}{g} \left(\frac{k_2}{r}\right)^2 \left(\frac{n_1}{n_2}\right)^2 a$$

where w_2 is the weight and k_2 the radius of gyration of the armature, and n_1 and n_2 the respective numbers of teeth on the axle gear and on the motor pinion.

The total retarding forces necessary are, therefore, for a trailer truck,

$$F_1 = T_1 + \frac{2w_1}{g} \left(\frac{k_1}{r}\right)^2 a \tag{30}$$

$$F_2 = T_2 + \frac{2w_1}{g} \left(\frac{k_1}{r}\right)^2 a \tag{31}$$

or, for a truck equipped with two motors,

[1] Compare Chapter II, "Rotational Acceleration."

$$F_1 = T_1 + \frac{2w_1}{g}\left(\frac{k_1}{r}\right)^2 + \frac{2w_2}{g}\left(\frac{k_2}{r}\right)^2\left(\frac{n_1}{n_2}\right)^2 a \qquad (32)$$

$$F_2 = T_2 + \frac{2w_1}{g}\left(\frac{k_1}{r}\right)^2 + \frac{2w_2}{g}\left(\frac{k_2}{r}\right)^2\left(\frac{n_1}{n_2}\right)^2 a \qquad (33)$$

For an ordinary pair of cast-iron wheels and axle, $\frac{k_1}{r} = 0.64$, and $\left(\frac{k_1}{r}\right)^2 = 0.41$; using these values in equations (30) and (31), and replacing T_1 and T_2 by their values found in equations (20) and (21), we have

$$F_1 = \frac{f_1 W}{4} \frac{(W + 3.28w_1)\, b + 2f_1\,(W_1 h + 2W_2 d)}{\left(W + 2f_1 W_1 \frac{c}{l}\right) b} \qquad (34)$$

$$F_2 = \frac{f_1 W}{4} \frac{(W + 3.28w_1)\, b - 2f_1\,(W_1 h + 2W_2 d)}{\left(W + 2f_1 W_1 \frac{c}{l}\right) b} \qquad (35)$$

Substituting these values in equation (28), we have

$$\tan \phi = \frac{2f_1}{f_2} \frac{W_1 h + 2W_2 d}{(W + 3.28\, w_1) b} \qquad (36)$$

Equation (29) may likewise be simplified by substituting the value of $F_1 - F_2$ from equation (28):

$$F_1 - F_2 = f_2\,(F_1 + F_2) \tan \phi \qquad (37)$$

whence

$$P = \frac{f_1}{f_2} \frac{W}{4} \frac{W + 3.28w_1}{W + 2f_1 W_1 \frac{c}{l}} \frac{(1 - f_2^2 \tan^2 \phi) \cos \phi}{\cos(\theta + \phi)} \qquad (38)$$

From this last equation it may be seen that, by hanging the brake beams between the wheels, and giving the proper angle of inclination to the hanger links, the pressure may be increased on the forward wheels of the truck, and reduced on the rear wheels, with corresponding changes in the frictional force produced. Reversing the direction of motion transposes the distribution of weight between the two axles of the truck, and also the actions of the hanger links, so that the greater pressure is always applied to the forward wheels.

The worst practical difficulty with the application of this method of compensation of the brake-shoe pressure lies in the fact that the angle ϕ must necessarily vary as the brake shoes

become worn; so that it is not possible to make the compensation the same under all conditions. Any desired amount may be secured up to the point where skidding occurs.[1] The practical values of $\theta + \phi$, the angle the hanger should make with the horizontal, range from 25° to 37°, depending on the length of wheel base and diameter of wheels.

Brake Rigging.—In any form of brake making use of the friction between the wheels and brake shoes, it is necessary to have a system of levers to transmit the force from the place where it is developed to the point of application. The general principles are the same for all brakes of this class: a comparatively small force is applied by air pressure at the brake cylinder, and it is increased considerably through the lever system. This is possible, since the total movement of the shoes to give the maximum pressure need be only a fraction of an inch.

The subject of leverage in brake rigging is primarily one of statics; but the question of space enters in making allowance for brake-shoe clearance, provision for wear of the shoes, wheels and joints, and the springing of members. The cylinders of standard air-brake apparatus are all designed to give a normal piston travel of about 8 in. The leverage ratio between the piston and the brake shoes varies to some extent; but good practice calls for values between the limits of 12 to 1 and 8 to 1. By this means the size of brake cylinder may be determined. For example, if the weight of a certain car is 50,000 lb., and 100 per cent. braking force is to be applied with a leverage ratio of 10 to 1, the force to be exerted by the piston is 5000 lb. With an emergency air pressure of 70 lb. per sq. in., this will require a cylinder with an inside diameter of 9.55 sq. in. Since the standard diameters of brake cylinders increase by increments of 2 in., a 10-in. cylinder will be required.

Having determined the proper size of cylinder, the brake rigging for the trucks and car body may be calculated. There are three different arrangements for applying the brake shoes: the brakes may be hung inside the wheels; they may be hung outside; or both may be used. The latter type is usually known as the "clasp brake." Of the first two, the inside hung brakes are preferable, for reasons already discussed. In some cases it may be advantageous to hang the shoes outside the wheels for structural

[1] For a further discussion of this topic, see *Transactions* A. I. E. E., Vol. XX, p. 264.

reasons. With either inside-hung or outside-hung brakes, there is an unbalanced pressure which must be opposed by a reaction from the wheel. This reaction is furnished by the brasses in the journal boxes. In the case of heavy high-speed trains, which have to be retarded rapidly, the braking pressures become excessive. This may cause the brasses to wear more on the side away from the brake shoes, and even force them out of position. To remedy this trouble, a number of railroads operating high-speed trains have adopted the clasp brake, for this type places equal brake-shoe pressures on opposite sides of the wheel, thus removing the reactions from the bearings.

Truck Brake Rigging.—In applying the braking force to the truck, it must be distributed equally to all of the brake shoes, or there will be danger of sliding the wheels. If it is desired to increase the braking force on the front wheels, this should be done

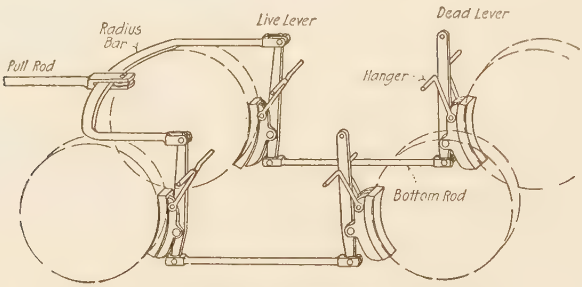


Fig. 88.—Truck brake rigging for electric car.

The force delivered by the pull rod is transmitted through the live lever and the bottom rod (sometimes known as the adjusting rod) to the dead lever, thus applying the brakes.

by giving the hangers the proper angle. The force can be applied to the four shoes separately, by having independent lever systems for each side, or together, through brake beams. These latter are used to a large extent on freight cars; but on electric motor cars there is seldom sufficient room for them with inside-hung brakes, so that separate levers are used, being connected together with a bar to which the main pull rod is fastened.

When brakes are applied to double-truck electric cars which must travel around sharp curves, the plain bar for connecting the truck brake levers together is sometimes not sufficient to provide for the excessive swiveling. In such cases the bar is made in the form of a circular arc, technically known as a "radius bar," and the brake pull rod is connected to it through a roller

working in a clevis. The truck can then swivel any needed amount without interfering with the action of the brakes.

The usual arrangement of the brake rigging without brake beams is shown in Fig. 88. The use of the radius bar and the relations of the levers may be clearly seen. It may be noted that, by fastening one end of the "dead lever" to the truck frame, the reaction of the brake shoe on the live lever is transmitted to the other shoe, so that the force applied gives double the braking effort produced on a single shoe.

Foundation Brake Rigging.—In Fig. 89 is shown a common arrangement of the essential parts of the brake rigging attached to the car body. The air pressure acting on the piston operates

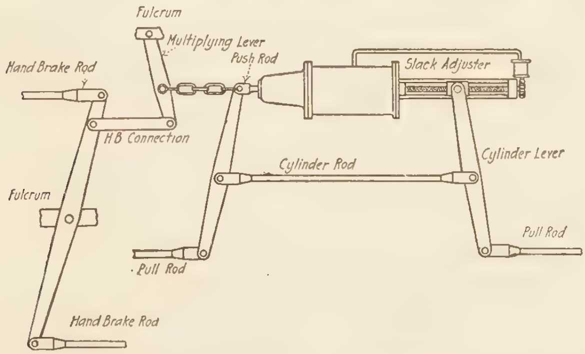


FIG. 89.—Foundation brake rigging.

A form of brake rigging in very common use. Note the method of connecting the hand brakes so as not to interfere with the action of the air-brake.

the push rod and the push-rod lever, and, with the aid of the cylinder rod, applies the requisite forces to the brake riggings of the two trucks. It is always desirable to provide hand brakes for emergencies, in case of failure of the air supply, or where it is necessary to hold the car after the air pressure has been cut off. This connection may be made to the push rod, as shown, the leverage on the hand-brake system being such as to produce the same total braking force as when air is used. Other arrangements may be made.

The calculation of the proper lengths of the various levers is simple after the brake-shoe pressures have been decided on. It will be different for each individual lever arrangement. To show the method of calculation, the determination for a typical car will be taken up.

Example.—A certain car, whose principal weights are given below, is to be fitted with brakes. The electrical equipment consists of two motors, both mounted on one truck, the other truck being a trailer. Connections for both air and hand brakes are to be provided, it being assumed that the platform leverage system of the hand brake is such that the average motorman can produce a force of 1200 lb. in the pull rod connected to the main lever system. It is desired to determine the lengths of all levers, and the forces in all parts of the brake rigging.

Weight of car body and apparatus supported thereon	40,000 lb.
Weight of motor truck	10,000 lb.
Weight of trailer truck	6,000 lb.
Weight of each motor	4,000 lb.

The motor truck is to have inside-hung brake shoes without brake beams. Both the live and the dead levers have lengths of 27 in., the brake shoes being hung 7 in. from the lower end.

The trailer truck is to have outside hung brake shoes with brake beams, the live and dead levers both being 23 in. long with shoes hung 7 in. from the lower end.

The braking force on the motor truck is to be 100 per cent. of the weight carried, and on the trailer truck 90 per cent. of the weight.

The weight on the wheels of the motor truck is

$$20{,}000 + 10{,}000 + 2 \times 4000 = 38{,}000 \text{ lb.}$$

or 9500 lb. per wheel. The brake-shoe pressure to be applied is, therefore, at 100 per cent., 9500 lb.

The weight carried by the wheels of the trailer truck is

$$20{,}000 + 6000 = 26{,}000$$

This corresponds to 6500 lb. per wheel. At 90 per cent. braking force the pressure per shoe is 5850 lb. Since a brake beam is to be used, the force for the two sides must be supplied at one point, making a total of 11,700 lb. on the brake beam.

The total braking power needed is

$$9500 \times 4 + 11{,}700 \times 2 = 61{,}400 \text{ lb.}$$

If a 12-in. diam. cylinder is used, a pressure of 60 lb. on the piston will give a total of 6780 lb. This will make the total leverage ratio

$$\frac{61,400}{6780} = 9.05$$

which is a conservative value for a car of this type.

On the motor truck, the dead-lever fulcrum being at the upper end, the force in the adjusting rod is

$$\frac{20 \times 9500}{27} = 7040 \text{ lb.}$$

With the live-lever fulcrum at the bottom, the pull at the top is

$$\frac{9500 \times 7}{27} = 2460 \text{ lb.}$$

The proof of this last calculation is that the sum of the force at the top and bottom of the live lever must be equal to the press sure on the shoe.

$$2460 + 7040 = 9500 \text{ lb.}$$

Since there is a duplicate set of shoes and levers on either side of the truck, the total stress in the pull rod is twice that found, or,

$$2 \times 2460 = 4920 \text{ lb.}$$

On the trailer truck, with the dead-lever fulcrum at the upper end, the force in the adjusting rod is

$$\frac{11,700 \times 23}{16} = 16,800 \text{ lb.}$$

In the live lever, with the fulcrum at the adjusting rod, the force at the top is

$$\frac{16,800 \times 7}{23} = 5100 \text{ lb.}$$

As above, this is proved as follows:

$$16,800 = 5100 + 11,700$$

At the brake cylinder, the force on the push rod is 6780; hence the force on the cylinder rod is

$$6780 = 5100 = 11,880 \text{ lb.}$$

The length a is therefore

$$\frac{6780 \times 30}{11,880} = 17.1 \text{ in. (in practice } 17\tfrac{1}{8} \text{ in.)}$$

and the length b is

$$30 - 17\tfrac{1}{8} = 12\tfrac{7}{8} \text{ in.}$$

For the cylinder lever, the length d is

$$\frac{4920 \times 30}{11{,}880} = 12.41 \text{ in. (in practice } 12\tfrac{3}{8} \text{ in.)}$$

and c is therefore

$$30 - 12\tfrac{3}{8} = 17\tfrac{5}{8} \text{ in.}$$

With a force of 1200 lb. acting on the hand-brake rod, which

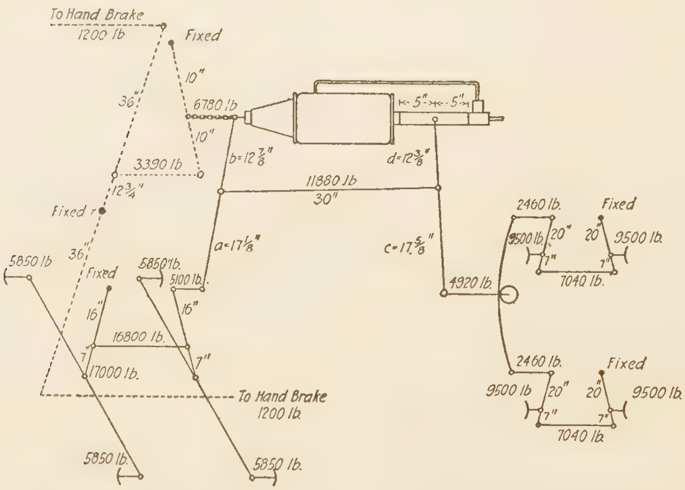


FIG. 90.—Distribution of forces in foundation brake rigging.

must be increased to 6780 lb., the force required at the end of the multiplying lever is

$$\frac{6780}{2} = 3390 \text{ lb.}$$

The length from the fulcrum to the point of connection is therefore

$$\frac{1200 \times 36}{3390} = 12.74 \text{ (practically } 12\tfrac{3}{4} \text{ in.)}$$

In order that the levers may be parallel when the slack adjuster is half way out, and the piston is at the end of its normal stroke, the length of the cylinder rod must be

$$20 + 5 + 5 = 30 \text{ in.}$$

A movement of ¼ in. at each shoe on the motor truck will give a movement at the push rod of

$$(\tfrac{1}{4} \times 2) \times \frac{27}{7} \times \frac{12.37}{30} \times \frac{30}{17.12} = 1.393 \text{ in.}$$

A similar movement of ¼ in. at each shoe on the trailer truck will give a movement at the push rod of

$$(\tfrac{1}{4} \times 2) \times \frac{16}{7} \times \frac{12.88}{17.12} = 0.86 \text{ in.}$$

The total movement of the push rod is

$$1.393 + 0.86 = 2.25 \text{ in.}$$

and, adding ½ in. for lost motion, the travel necessary for the push rod to apply the maximum braking force is approximately 2¾ in.

Automatic Slack Adjuster.—The amount of air needed for producing a certain cylinder pressure depends on the piston travel, so that it is desirable to keep this as short as possible. With the automatic brake, where the cylinder is supplied from an auxiliary reservoir of small capacity, excessive piston travel will result in reduced cylinder pressure, and consequently smaller braking effort. The best operation is obtained when the piston travel is just sufficient to allow proper clearance of the shoes when the brakes are released. On standard equipments this calls for a running travel of about 8 in. Any greater movement simply calls for more air or for less efficient braking.

Various forms of automatic slack adjusters are on the market. The best known of these is shown in Fig. 89. A small connection is made through the brake-cylinder wall at a point determined by the maximum desirable piston travel. When this is exceeded air is admitted to the tap, and serves to operate a ratchet, changing the position of the lever, as indicated in the diagram. Each time the brakes are applied when the travel is greater than the desired amount, the ratchet will move one notch, until the excess has all been taken up, after which no further action of the slack adjuster will take place until the slack has again passed the limiting value, and the piston travel has become too great.

Methods of Supplying Braking Force. Hand Brakes.—The brake rigging described will work equally well with any available

force that can be applied in the proper amount, and with proper control. Two methods of operation have been suggested—manual and air pressure being used. With hand brakes, the force is applied to a brake staff by means of a cranked handle or hand-wheel turned by the motorman. The staff carries at its lower end a chain which is attached to the pull rod connecting to the foundation brake rigging. By rotating the brake staff the chain is wrapped about it, thus applying the braking force to the rigging. If the car is heavy, and the necessary retarding force is large, it is sometimes impossible to get sufficient leverage with this arrangement. To increase the pull, the bottom of the brake staff may carry a gear, the chain connection to the pull rod being made through the meshing gear. The force may thus be increased to any desired value. A limitation may be seen in various forms of high-ratio hand brakes, in that, if designed to give the maximum braking force when applied by the average motorman, there is a great risk of skidding the wheels when operated by a stronger man. This is something which cannot be taken care of in the design, and may result in the use of hand brakes of less power merely to obviate this danger.

In the operation of hand brakes, it is necessary, as in any case, to have a certain amount of "slack" in the rigging. This is needed to keep the shoes away from the wheels when the brakes are released. The ordinary motorman, in making a stop, desires to apply the brakes as soon as possible after the signal has been given, or the proper place for their operation has been reached. In order to prevent loss of time in making the application, it is often the custom among motormen to run the cars with the slack all taken out of the brake rigging, the shoes being as near the wheels as possible without applying the brakes. This is done by winding the spare chain on the brake staff, and holding the handle in that position continually. When operating in this manner, it is almost impossible to keep from having some friction of the shoes on the wheels. This, in effect, is the same as increasing the train resistance; and it requires additional power from the electric circuit. In certain cases where air brakes have been added to cars already in use with hand brakes only, it has been found that there has been a marked decrease in the power consumption, sometimes amounting to as much as 15 to 20 per cent.

Air Brakes.—Of all the forms of power brakes which have been developed, the one which has met with the greatest success and has been most widely adopted, is that in which the braking force is produced by means of compressed air. Generally speaking, compressed air is admitted to the brake cylinder, and the piston operates a push rod connected to the rigging. The principal difference in various types of brakes is in the methods by which the admission and release of air to the cylinder is controlled. The two methods in general use are the "straight" and the "automatic" systems. In the former, air is applied directly to the brake cylinder from a main reservoir; in the second, it is supplied to the cylinder from an auxiliary reservoir, the main air pressure being used to control the admission of air to and from the latter, and the release of the air from the brake cylinder to the outside atmosphere.

Methods of Compressing the Air.—Another way in which systems of air brakes differ is due to the methods in use for supplying the compressed air. The simplest arrangement is to provide large stationary compressors at suitable points along the railroad. These plants continuously charge stationary reservoirs of large capacity. Each car is provided with a storage tank, which may be charged from the stationary reservoirs as needed, the operation taking but a few minutes as the car reaches the charging station. In order to reduce the size of the car reservoir, the air is stored at high pressure (about 300 lb. per sq. in.). For use in the cylinders, this is reduced to about 45 lb. per sq. in., which causes a certain loss in efficiency.

The more common method of supplying the compressed air is by means of individual compressors, located on the cars or locomotives. For steam service, the compressors are driven directly by steam from the boiler, there being one or more installed on each locomotive, depending on the capacity required. For service on electric roads, the steam pump is replaced by one driven either from gearing connected to the axle, or by an individual electric motor. The axle-driven compressors were favored in the early period of air-brake operation on electric roads; but, owing to a number of difficulties in construction, and high maintenance costs, they have been almost entirely susperseded by motor-driven compressors.

The motor-driven compressor may be either a simple or a two-stage air pump of the reciprocating type, operated direct or

through gearing by a small series motor, in the case of direct-current or single-phase roads; or by an induction motor on three-phase lines. In systems using individual compressors, where the reservoir can be charged as often as required, the pressure range is between 50 and 90 lb., the limits between the maximum and the minimum values usually being about 20 lb. (*e.g.*, between 70 and 90 lb. is the range on many systems).

To keep the pressure in the reservoir within the proper limits, intermittent operation of the air compressor is necessary. The action is controlled automatically by some form of governor which connects the motor to the line when the pressure has fallen to the minimum limit, and opens the circuit when it has been increased to the maximum. Various types of governor are in use, but the basic principle, as stated above, is the same in all.

Straight Air Brakes.—The simplest method of supplying the air to the brake cylinder is obviously that in which it is admitted directly from the main reservoir. The control for this type of brake consists essentially of a valve operated by the motorman, which can connect the cylinder to the main reservoir, can disconnect it and retain the air, or can release the air completely from the cylinder by connecting it with the atmosphere.

For single-car operation, the straight air brake is ideal, for the motorman can graduate the amount of air admitted to the cylinder and thereby adjust the braking force to obtain uniform retardation in spite of the variable coefficient of friction. As the length of the train is increased, difficulty is experienced in getting uniform application of the brakes. All the air which enters the cylinders must flow from the main reservoir on the forward car or locomotive, through the controlling valve, and then through a train pipe to the brake cylinders on the individual cars. It is evident that the pressure will build up at the front end of the train first; and that a considerable time will elapse before the brakes are applied with full force on the last car of the train. This variation in force at the instant when the brakes are applied may cause trains to break in two, resulting in serious accidents; and at best imposes severe strains on the drawbars.

Automatic Air Brakes.—To obviate the troubles incident to the use of straight air brakes on trains of considerable length, the automatic air brake was developed. In this system the train pipe does not feed directly into the brake cylinders, but is used to charge a main reservoir on the locomotive and a set of auxiliary

reservoirs, one of which is located on each car. In the normal running position, all of the latter are fully charged to the train pipe pressure, and the brake cylinders are open to the outside atmosphere.

These relations are controlled by a device known as the "triple valve," shown in Fig. 91, which automatically makes the proper connections between the train pipe, the auxiliary reservoir, the brake cylinder, and the outside atmosphere. It is evident that a triple valve is a necessary part of the equipment of each car in the train.

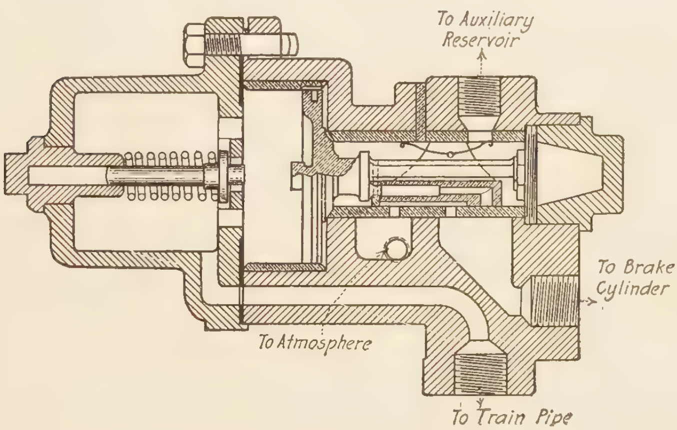


Fig. 91.—Plain triple valve.

As shown, the brake cylinder is exhausting to the outside atmosphere, and the auxiliary reservoir is being charged from the train pipe. This is the release or running position. A reduction in train pipe pressure causes the slide valve to move to the left, closing the connection between the train pipe and the auxiliary reservoir, and connecting the latter to the brake cylinder, the exhaust being closed at the same time.

To apply the brakes, the train pipe pressure is suddenly reduced, which causes a movement of the triple valve, disconnecting the auxiliary reservoir from the train pipe, and connecting it with the brake cylinder, meanwhile closing the exhaust connection. This causes the air to flow from the auxiliary reservoir to the brake cylinder, applying the brakes. Various improvements have been made from time to time to increase the rapidity with which the train-pipe pressure is lowered, and to make the movement of the triple valve with a minimum reduction in pressure. In the well-known "quick-action" brake, which is in use on a large proportion of the steam roads, the train pipe is vented directly into the brake cylinder by the movement of

the triple valve. In this way the reduction in train-pipe pressure can be made in a very short time, requiring only a few seconds for the longest freight trains in operation. In making an ordinary or "service" application, the full pressure available from the auxiliary reservoir is not needed. When the desired amount of air has been admitted to each brake cylinder, its triple valve is closed. To produce this effect the train-pipe pressure need only be lessened a small amount; in the standard types of brake this reduction must not exceed about 15 lb. With a greater drop in the train pipe the "emergency" application occurs, in which the train pipe is fully vented to the atmosphere or to the cylinders, and the full pressure from the auxiliary reservoir is applied to the brakes.

To release the brake, the engineer's valve is moved to such a position as to admit air from the main reservoir to the train pipe. This increase in train-pipe pressure changes the position of the triple valve so as to close the connection between the auxiliary reservoir and the brake cylinder, connecting the former to the train pipe. This recharges the auxiliary reservoir. At the same time the brake cylinder is connected to the atmosphere, which releases all the air and removes the pressure from the piston and from the brakes.

A modification of the quick-action brake, known as the "high-speed" brake, has been developed for use on fast passenger trains. In the design of this brake, account is taken of the fact that the coefficient of friction is less at high speeds. The train-pipe pressure in this type is higher than in the quick-action brake, being in the neighborhood of 110 lb. When the emergency application is made, the full pressure is applied from the auxiliary reservoirs to the cylinders, producing a braking force which, although not sufficient to cause sliding of the wheels at the high speed, would almost certainly do it before stopping the train. To prevent such a result, the pressure is lowered gradually, by means of an automatic reducing valve on the car, to the emergency standard of 60 lb.

Electropneumatic Brake.—Although the quick-action and the high-speed brakes have been very satisfactory in general service, conditions arise in connection with the operation of heavy, fast trains, where the control they exercise is not sufficient. Even with the quick-action brake, there is a certain time lag between the movement of the engineer's valve and the application of the

brakes on the rear car of the train. Where the trains are short, or where the speeds are low, this will cause no difficulty in operation. With long, high-speed trains there is considerable surging of the cars, and strain on the draft rigging. Further than this, the time required for the full application of the brakes makes the total distance from the braking signal to a stop materially longer than if the brakes were all set simultaneously. A certain time element is unavoidable, for the air cannot flow from the auxiliary reservoir to the brake cylinder instantaneously; but beyond this, it is desirable to eliminate the lag. This is accomplished by the use of the electropneumatic brake. In this type, the ordinary features of the automatic brake are retained, but the application of the pressure is governed by an electric circuit, in a manner somewhat similar to that of the electropneumatic control of the motor circuits in multiple-unit operation. A special form of triple valve is used, in which the admission of air to the brake cylinders is governed by electromagnetic valves. By proper combinations of electric circuits the brake cylinder pressure may be built up to the maximum, may be held in the cylinders, or may be wholly or partially exhausted. This latter feature is of great importance, since with the ordinary automatic brake there is little opportunity to provide a graduated release.

A comparison of the action of the two types of brake is shown in Fig. 92.[1] In the pneumatically controlled brake, the stop is made in 40 seconds from the time the brake application was begun, bringing the train to rest in a distance of 1290 ft. In this operation a graduated action was obtained by increasing the train-pipe pressure to release the brakes and then partially reapplying them. In comparison with this, the electrically controlled brakes brought the train to rest after 20 seconds, or one-half the time required for the pneumatic, the distance taken being 700 ft. In the operation of the electrically controlled brake, a much more effective graduation of the release was obtained, there being two partial reductions of pressure. The result can be seen in the more uniform slope of the speed–time curve. Due to this feature, the maximum braking effort can be increased to a value which would be dangerous for the ordinary automatic brake. It should be noted that the final pressure at the end of the stop is

[1] Figs. 92 and 93 are from an article by W. V. Turner, *Electric Journal*, Vol. VIII, p. 905, Oct., 1911.

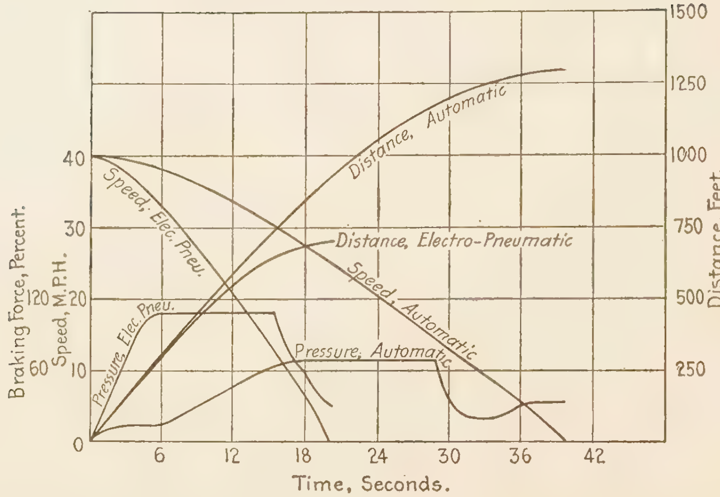


FIG. 92.—Service stops with automatic and electropneumatic brakes.

Note that the pressure builds up much more rapidly in the electropneumatic application; also that the release is gradual, while in the automatic application the brakes were released and then re-applied to reduce the pressure.

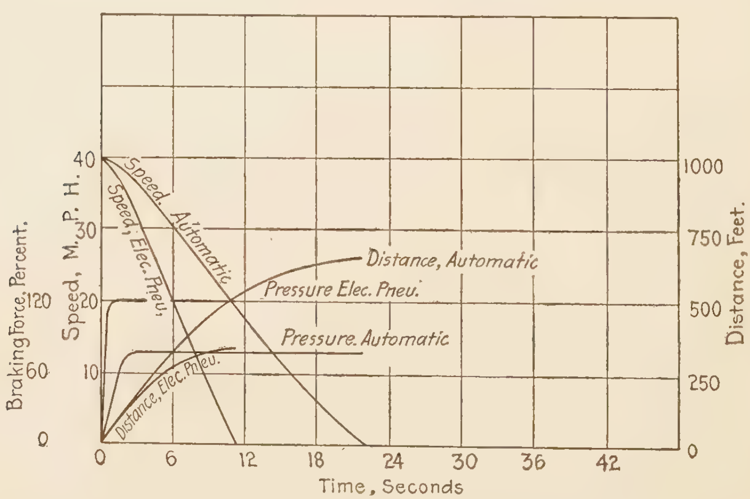


FIG. 93.—Emergency stops with automatic and electropneumatic brakes.

In addition to using a higher braking force, it is possible to build up the pressure more rapidly with the electropneumatic brake, resulting in a considerable reduction both in time and distance required for stopping a train.

less with the electropneumatic control than with the common type.

In emergency stops the advantage of simultaneous action of the brakes on all the cars is much greater than for service applications. A typical comparison of emergency stops is shown in Fig. 93, which has been plotted to the same scales as Fig. 92. It may be seen that the total distance for the stop is 300 ft. less for the electric brake, or only slightly over half that for the pneumatic. The time for stopping the train is likewise decreased from 22 seconds to 11 seconds. The use of the electric control makes possible a considerable reduction in the distance interval which must be allowed between trains for safety, so that track capacity may be materially increased.

Combined Straight and Automatic Brake.—Many electric roads operate their cars singly for the greater portion of the time, but occasionally run trains of two or three cars. For single-car service the straight air brake gives all the desired features and is easier to manipulate than the automatic. But when cars are coupled together, the use of the straight air brake, even on comparatively short trains, leads to the difficulties due to slow transmission of the braking force to the rear of the train. For such cases it is possible to have a combined equipment, which for normal operation acts as a straight air brake, but may be quickly converted into an automatic brake by the change in a few valve connections. A number of variations in the arrangement of the valves is possible, and several types of combination brake are in use.

Vacuum Brake.—Although the air brake is in almost universal use in this country, it has a competitor in Europe in the vacuum brake. In this type the principle of operation is almost identical with that of the air brake, but the compressed air is replaced by a partial vacuum, produced by a pump somewhat similar to the ordinary air-compressor. Since the pressure in the brake cylinder depends on the unbalanced action of the external air on the piston, it follows that the maximum force which can be obtained is 15 lb. per sq. in. In order to get the same brake-shoe pressures as are ordinarily in use, the size of cylinders must be considerably increased. In general, the operation of this brake is inferior to the modern air brakes described above.

Electric and Magnetic Brakes.—A number of attempts to utilize electric energy for the braking of trains have been made

from time to time. The simplest of these consists of a disc, fastened to the axle, and a circular electromagnet attached to the truck. The magnet, when energized with current from the trolley wire, may be made to bear against the disc. This type of brake was developed a number of years ago; but it never was very successful, and is now obsolete. A much simpler arrangement is to reverse the car motors and connect them to the line. This produces a counter torque, giving a powerful retarding effort. Both of these methods of braking require the use of electric energy from the line, and the second increases the duty of the motors.

It has already been shown that a moving car possesses a considerable amount of stored energy, due to its velocity. It would seem desirable to utilize this in stopping the car in some other way than to waste it in heating the brake shoes and wheels. If the motors can be made to reverse their usual functions and act as generators, they will convert the kinetic energy of the moving train into electricity, which may be returned to the line or used for some other purpose. The greatest obstacle in the way of returning energy with ordinary equipments is that the series motor does not readily lend itself to this use. If allowed to operate without change of connections, it cannot be made to exert a counter-torque, since the speed increases indefinitely as the load is reduced. On the other hand, if the field is reversed, the counter e.m.f. will be in the same direction as the line e.m.f., so that the motor will give a counter-torque, but with additional current from the line. To make the series motor available for this kind of braking, and to return energy to the constant-potential trolley circuit, it is necessary to add a shunt field. This complicates the construction of the motor and of the controller to a point where it is not ordinarily considered feasible.

It is possible to short-circuit the motor on itself, after the line circuit has been disconnected. In this case the machine acts as an ordinary series generator, and will deliver a current dependent on its characteristic and the resistance in the external circuit. By properly choosing the resistance, the power delivered can be adjusted as desired, with a corresponding retardation of the train.

To adapt this method of braking to a set of motors with series-parallel control, it is necessary to reverse the motor fields so the e.m.f. will be generated in the proper direction. The resistance

may be chosen to give the desired retardation. This is a method of emergency braking which is always available on any car equipped with two or more motors and series-parallel control. The machines may be disconnected from the line, reversed and thrown to the parallel position. They will then generate e.m.f.'s in the same direction; but, since the magnetic circuits are never absolutely identical, there will be more residual magnetism in one or the other machine, so that it will overpower the other and operate it as a motor. The two e.m.f.'s will then be in series, and a considerable current will flow around the local circuit, whose value will be determined by the speed of the car and the resistance. The power required for this action is taken from the momentum of the car, and tends to reduce the speed. In the case of a four-motor equipment, with the ordinary platform controller, it is unnecessary to throw the handle to the parallel position, for the pairs of motors are placed in parallel through the reverser. All that is needed is to change the connections by throwing the reverse lever. It is obvious that if the car is moving backward, the braking effect will be produced with the controller thrown to the forward position.

With some types of controller the only resistance will be that of the motors and the wiring, so that the current and the braking effort will be large, but if the method is used for emergency stops only, this will not occasion any difficulty. If the torque developed is so great as to cause the wheels to slide, the e.m.f. generated by the motors falls to zero, and the torque consequently disappears. The motors will then revolve, again producing a braking effort.

Newell Magnetic Brake.—A form of brake, depending on the same principle, but using it much more effectively, was developed about ten years ago, and placed on the market under the name of the "Newell" brake, from its inventor. In this type, shown in Fig. 94, the current from the motors, acting as generators, is passed through the coil *a* of the magnet, *b*, pulling it against the track and providing a powerful braking effort. The movement of the magnet downward has also the effect of operating the lever system, thus applying the brake shoes to the wheels. The effect of the magnets is twofold; in addition to producing a braking effort in themselves, they pull the entire truck down on the track with increased force so that a greater total braking effort may be applied to the wheels.

An ingenious feature of the Newell brake is that the energy wasted in resistance, instead of being dissipated to the air beneath the car, is utilized for heating by having the resistors put inside the car body in place of the ordinary electric heaters. Both the loss at starting and while braking are used to heat the resistors; and the material of which they are made is such as to store the heat and give it out at a nearly uniform rate. With city cars making frequent stops, the amount generated in this manner is ordinarily more than sufficient to keep the temperature as high as is usual with the ordinary methods of heating. While there is no reason why the starting loss should not be used in the same way, when this system of braking is not employed, it is not customary to do so. For service in summer

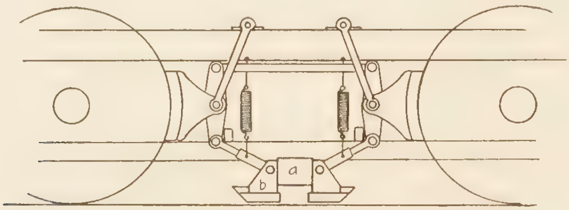


Fig. 94.—Newell electromagnetic brake.

Current delivered by the car motors acting as generators is passed through the coil *a* of the electromagnet *b*, causing a braking effort.

a duplicate set of resistors is placed beneath the car in the usual position.

With this type of brake it is entirely practical to obtain retardations of 3 miles per hr. per sec. and over. The greatest operating difficulty with the Newell brake, as with all types utilizing the motors to generate current in a local circuit, is that when the rotation of the wheels ceases the braking effort stops. It is, therefore, necessary to use the hand brake, or some other form of power brake, to hold the train after it has been brought to rest, which is an undesirable feature. Another objection is that the motors are working a greater portion of the time, so that the effective heating (r.m.s.) current is increased. If they are of more than sufficient capacity to make the schedule, this will have but little effect; but if already worked to the heating limit, the imposition of the added load will force them beyond their continuous capacity and cause damage. This point should be given careful study in case any such form of brake is to be applied.

Momentum Brakes.—The inertia of the train may also be used to operate a mechanical brake. Momentum brakes have been designed in which the shoes or drums are brought in contact by means of some form of friction clutch. This type has never been very successful, and its use has been extremely limited. It is difficult to make any such form of brake operable for more than a single car, which limits its application at once. It is extremely doubtful whether any such device can ever find a wide use.

CHAPTER VIII

CARS AND CAR EQUIPMENT

Classification.—Cars for railway operation may be very broadly divided into two main groups: those for freight or express service and those for the transportation of passengers. Cars of the former type have been standardized to a large degree, and their design must conform to certain rules adopted by the Interstate Commerce Commission and the Master Car Builders' Association. Passenger cars, on the contrary, are not subject to such rigid supervision; and, especially in the case of electric roads, there is wide divergence in their design. It is with those of the latter type that this chapter treats.

The development of car design for electric railway service has very closely followed the growth of the different classes of roads, as enumerated in Chapter I. Passenger cars for electric railways may therefore be roughly classified as follows:

1. Cars for city and suburban service.
2. Rapid transit cars (elevated and subway).
3. Interurban cars.
4. Trunk-line coaches.
5. Special service cars.

The latter two types need not differ in any particular from standard cars for steam railway service. On such trunk lines as have been or may be electrified, our present experience indicates that all motive power will be supplied by independent locomotives, so that no electrical equipment on the cars is needed for successful operation. In case a general electrification of any railroad is made, it may be desirable to include such minor details as electric light and heat, and possibly bus lines and control cables so that the motive power may be subdivided and placed at intervals throughout the length of the train, and handled with multiple-unit control. Such changes are of minor importance, and need not be considered, since they do not require any modification of the design.

Cars of the types for operation on city surface railways ("tramways") have undergone a gradual development from the same beginnings as the steam railroad coach; but the necessities of the service have produced a radically different structure. Although street cars have been passing through a process of evolution for the last 60 years, there is today less uniformity in design than ever before. This is largely due to the changing conditions of operation on large city roads, which are forcing them to provide increased facilities and at the same time receive less return on the investment. In order to meet this situation, car builders and railway companies are today developing radical designs with the object of better and more economical operation.

Since they run almost exclusively on private right-of-way, cars for elevated and subway service are not subject to the same limiting conditions as to size and weight as are surface cars. Their design approaches more nearly that of standard steam coaches. The main difference lies in the fact that to secure rapid movement the doors must be specially designed to facilitate passenger interchange.

For interurban service the cars may be quite similar to standard railway coaches. Since they are ordinarily operated in one- or two-car trains, it is often essential that a single unit combine the functions of coach, smoker, baggage car, and sometimes express and mail. As the traffic on roads of this class is largely local, more attention should be paid to the design of doors than in cars for through trunk-line traffic.

Structural Classification and Development.—Considering cars from a structural standpoint, they may be classified according to form or type, to material, or to framing and construction. They naturally divide themselves into two types: closed or "box" cars, and open or "summer" cars.

The early designs of street cars were of the closed body or "box car" type; and most of the more recent developments have been in this class. The first cars were direct adaptations of the stage coach for service on railways or tramways. While those for steam roads were soon increased in size, and before long crystallized into standard designs of considerable capacity, the street cars, due to the limitations of animal power, tended toward extremely light construction. The one-horse "bobtail" car was the first development for purely city service. Cars of this type were usually about 12 ft. long, were single ended, and

were arranged for operation by one man, the driver. The floor plan of a car of this type is given in Fig. 95. With the growth of cities and the corresponding development of the street railway business, came a demand for designs of increased capacity. This led to the construction of cars of about 18 to 20 ft. length of body (Fig. 96), usually drawn by two horses. In some cases these were handled by the driver alone, but more frequently they were arranged for two-man operation. Due to the necessity of light weight, no further development was possible so long as animal power was retained. The use of the cable did not change the situation to any extent, since its strength was limited, and the car weight had to be kept a minimum.

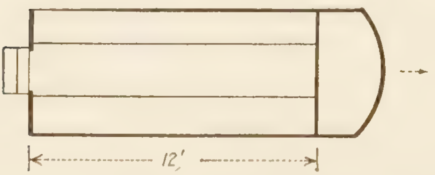


Fig. 95.—Floor plan—one horse car.
This type of car was in use in a large number of American cities from about 1850 to as late as 1900.

The advent of electric power changed the entire situation. Although most of the early electric cars were the same ones that had previously been used with horses, it was almost immediately seen that the limit to size had been removed. A gradual increase began at once; but before long the limit of capacity for a single truck caused the adoption of longer bodies, supported by two swiveling or "bogie" trucks. This has become the standard for nearly all classes of service, the small single-truck car having now been superseded in all important cities, except for special service or on lines of extremely light traffic.

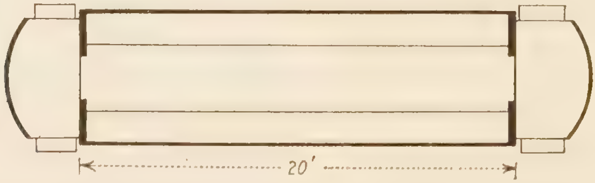


Fig. 96.—Single-truck horse car, or early electric car.
A later model than that shown in Fig. 95, designed to be drawn by two horses. Many of them were remodeled and fitted with electric motors between 1890 and 1900.

The open car, Fig. 97, has always been a favorite with the riding public. It is only applicable for city service, being unsuited for high speeds or for long runs. It usually consists of

a wooden underframe, supporting a skeleton side framing with a light roof. On account of the lack of side bracing, it is structurally weak. The seats are ordinarily transverse benches extending the entire width of the car, and access is obtained by a step or running board at either side. Such an arrangement is dangerous for the passengers. It may be shown that it is slower to load and unload than the modern types.

While the open car may be justified in southern climates, where it can be in service the entire year, its use in northern cities is limited to a season seldom over six months long. This requires

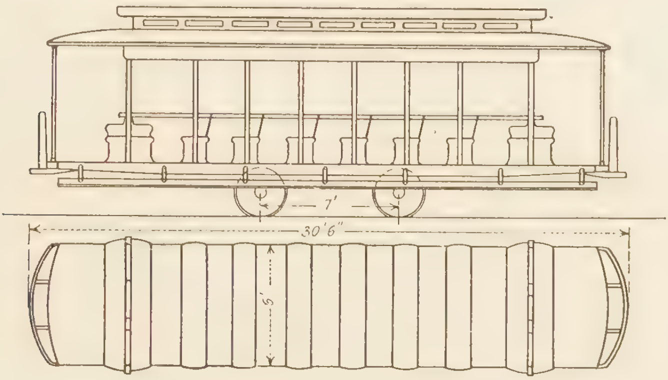


FIG. 97.—Single-truck open car.

This type of car has been in use, both with horses and with electric motors, from the early days of street railways up to the present time.

a duplication of equipment. Some of the smaller roads reduce the capital expense by using the same trucks under both open and closed cars, transferring them at stated dates. This practice is open to considerable objection.

In order to meet the demand for the open car, and at the same time reduce the total cost of equipment, a new type was designed about ten years ago, known as the "convertible" car. In this the window sash and side paneling could be removed or else stored in the roof, so that the same body was available for either summer or winter service. Due to the inherent structural weakness and the difficulty of getting a tight construction for winter service, this car never had a great popularity with the street railways.

A compromise between the closed and the open types was finally made in the so-called "semi-convertible" car. This is

practically a closed car, but with larger windows than ordinary. The sash are either stored in the roof or in pockets in the side walls beneath the window sill. With the use of transverse seats, this type meets most of the demands of the riding public, and is adaptable to any of the methods of fare collection which have become standard in the last few years.

In the larger cities, the demand for units of very great capacity has become pressing in the past few years. Double-truck cars of the largest types have been unable to meet the needs where street congestion is great. At the present time, several cities are making experiments with double-deck cars to obtain maximum capacity with minimum space in the street. These have not been in service for a sufficient length of time to demonstrate their worth, but it is probable that their use will be extended where congestion is a maximum.

Another attempt to increase capacity has been made by the use of articulated cars. In the types which have been brought out, two small car bodies have their platforms removed and are joined by a flexible unit, so that the combination forms a single car. The entrance is placed in the flexible platform, and the exits are at the ends.[1]

Still another method for getting increased car capacity is the use of trains of two or more units. These may consist of one motor car and trailers, or two or more motor cars, operated by multiple-unit control.

Exceptional conditions have from time to time brought forth special designs of cars. Among these may be mentioned the "California" type. This car is a combination of closed and open car. In most of the designs the center portion of the body is enclosed while the end portions of the car are open. It is a favorite where the climate is mild, but is changeable, as in California. It is not likely to ever have a very wide field of application, since in localities where the weather changes are sudden and severe the car has practically one-half its capacity idle at all times.

Materials of Car Construction.—All the earlier cars for every class of service were built exclusively of wood. This is the cheapest available material, and its fabrication does not call for expert design. Within the last ten years the price of wood has

[1] For a more complete description, see *Electric Railway Journal*, Vol. XLI, p. 583; Mar. 29, 1913.

risen considerably, so that the advantage of low cost is less than formerly. Steel as a material for cars has been making rapid progress, for, although the first cost is greater, the depreciation is less. Steel cars are more reliable and are nearly free from fire risk. In collisions they stand up better than those built of wood. The advantages of wood as an interior finish are obvious; and some roads seek to retain the good points of both materials by adopting a semi-steel construction, in which the main framing is of steel, the details and finish being of wood. This makes a cheaper structure than the all-steel car, but the fire risk is greater and the depreciation usually more. The use of the all-steel car is increasing rapidly, and it is quite possible that it will be required by law on all main line passenger roads within a few years.

Framing.—There are three general methods of supporting the car body. The oldest and most used is to build a heavy underframe or platform, which is strong enough and sufficiently rigid to carry the entire superstructure. This construction produces a very satisfactory car, whether the framing is of steel or of wood, but it is often unnecessarily heavy and correspondingly costly. The expense incident to hauling needless dead weight may be a large amount on a road operating many cars; and the framing should be so designed as to reduce this extra weight to a minimum. This can be done by carefully determining the stresses in all parts and designing the members only sufficiently heavy to give a proper factor of safety. When the entire strength is in the floor or bottom framing, the vertical stiffness is not great, and must be supplied either by making the longitudinal members heavy, or by providing tension members beneath the sills.

A second method of framing was invented by George Gibbs, and first used in the design of the original steel cars for the New York subway.[1] The principal difference in this design is that the main longitudinal members are located at the top of the car, the weight being carried by the sills through the medium of the window posts. The floor framing is light, having only enough strength to support itself. The window posts are heavy enough to transmit the load to the bolsters. By the adoption of this construction, the total weight of the members may be less than

[1] A complete description of the original subway cars is given in *American Engineer and Railroad Journal*, October, 1904.

with the rigid underframe. It is obvious that this is only applicable to cars built wholly or partially of steel; but with this type of framing they may be made nearly as light as those of wood.

A third method of construction makes the side sheathing of the car furnish a large portion of the vertical stiffness, the design being quite similar to the familiar plate girder bridge. By thus utilizing the side sheathing, a maximum weight efficiency may be obtained. Cars of this type have been designed for a considerable number of city roads, for a few interurbans, and for nearly all of the elevated and subway lines. The excellence of this framing, and the comparatively small amount of dead weight, is increasing its popularity; so that it is likely to become standard for many types of cars for different classes of service.

Roof Framing.—In the early designs of cars, the roofs were made independent of the bodies, and were of the lightest construction, often being flimsy. Operation by electric power with an overhead trolley made it necessary to considerably strengthen the roof framing. At the same time, it was felt that the flat roof design of the old standard horse car did not permit good ventilation. A somewhat radical change was made by the addition of the "monitor deck," the type which is familiar on steam railroad coaches. After a long period of use, it has been found that the monitor roof, with movable sash, does not offer a satisfactory solution of the ventilation problem, and that the break in the roof framing inherent to the design makes a weak structure. Ventilation has been taken care of by various systems, some dependent on the motion of the car to draw the used air out through special ventilators, while in others air is circulated by means of motor-driven blowers. The application of these devices has removed the primary need for the monitor deck; and the secondary purpose, to furnish light, has been all but defeated through the use of colored glass.

A solution of the roof problem which has been satisfactory was advanced a few years ago, and is being adopted in many of the new designs. The monitor is omitted entirely, the roof being made in the form of a flat arch, rounded at the ends to form a platform hood. The use of steel angles, bent to the proper shape, for carlines, results in stiffening the roof to a marked degree, and with a reduction in weight over the monitor design. The natural lighting of the car need not be interfered with, since the form of the roof allows the windows to be made somewhat

higher. A further development is to continue the window posts upward, bending them in a complete arch, and making them serve for carlines. This still further strengthens the framing, making the entire structure more nearly one complete unit.

In any of the arch-roof cars the ventilation must be taken care of by some form of forced air circulation. Careful design has given much better results in this respect than were possible with the monitor roof; and the general appearance of the car, both interior and exterior, is at least as good as that of the earlier type.

Door Arrangement.—Where the stops are infrequent, as in trunk-line service, the arrangement of the car interior is generally for the comfort of the passengers during the journey, any extra time consumed at stops being of minor importance. With city surface lines and rapid transit roads, however, the main object is to obtain a fair schedule speed with a maximum number of stops. In such cases the length of ride per passenger is comparatively short, and a certain amount of comfort may be sacrificed in order to reduce the duration of the trip. For this class of traffic the arrangement of the car, both as regards the seating and the doors, should be made to facilitate the movement of passengers when entering and leaving. The earliest types of car for this service were on the same general plan as the ordinary steam coach, having doors at each end, and seats arranged either transversely, or longitudinally, as in Fig. 96. In the older cars, the platforms were entirely open; but owing to public demands, most of them have been enclosed with permanent vestibules for the past ten years. The first effect of this change was to attract a large number of passengers to the platforms, where they rode by preference. Naturally this tended to congest the entrances, and to make rapid loading and unloading difficult. In some cities, such use of the platforms by passengers has been prohibited. Although this aids to some extent it still is not the best arrangement for rapid interchange. A simple expedient is to use one end of the car for entrance only, and the other for exit. This establishes regular paths for the movement of the passengers, and aids greatly in reducing the time of stops. Many objections to this method of operation have been raised, the principal one being that passengers must either get on or off the car quite a distance from the street crossing, which may necessitate walking through mud or snow. In some cities a compromise is made by regularly

employing the scheme mentioned above, but allowing passengers to use either platform as an exit at the discretion of the conductor. With this modification, the efficiency of the method is reduced considerably.

The proper design and location of the entrance and exit doors has a marked effect on the rapidity of loading and unloading.

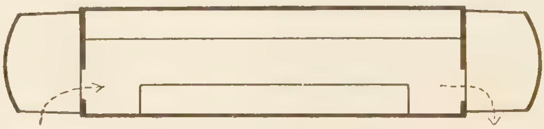


Fig. 98.—Accelerator car.

An early attempt to prevent crowding of the entrance and exit, and to reduce the time of stops. Suitable for single-end operation only.

The single, narrow swinging door of the steam coach limits the speed with which passengers can enter or leave the car. If doors of this type are used for street cars, a long time will be needed at stops. An early attempt to aid the passenger distribution is the

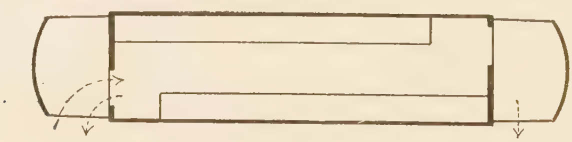


Fig. 99.—Semi-accelerator car.

A modification of the type shown in Fig. 98, arranged to allow double-end operation.

Brownell "accelerator" car, shown diagrammatically in Fig. 98. In this the doors were placed at one side of the center, nearest the entrance step. This prevented any persons who might be standing on the platform from interfering with the movement of pas-

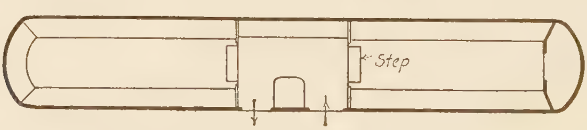


Fig. 100.—Center-door car.

A recent type which, with a few minor modifications, has been adopted in a number of large American cities.

sengers boarding the car. Such a design is only applicable where the cars always run in one direction. Where they must run either way, the "semi-accelerator" car, Fig. 99, could be substituted.

As a further aid to rapid movement, center doors may be used, either alone, as in Fig. 100, or in conjunction with the end doors.

The former possess many practical advantages, due to the fact that the passenger movement may always be under the eye of the conductor, and he may be held responsible for any accidents. The great operating objection to the center-door car is that it is more difficult to establish regular paths for the passengers than in the end-door cars. By careful training of the conductors it is possible to largely prevent this trouble.

Seating Arrangement.—The influence of the seating plan on the rapidity of loading and unloading is quite marked. The older

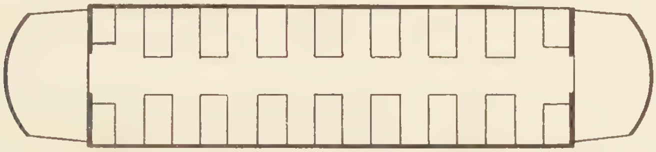


FIG. 101.—Cross-seat car.
A design widely used about 1900; an adaptation from steam railroad coach designs.

types of street cars were nearly all equipped with longitudinal seats on either side of the center aisle, running the entire length of the car body (Figs. 95, 96, 98, 99). While this plan is fairly satisfactory when there is no crowding, it becomes bad with a standing load. It is unpleasant for the seated passengers, and inconvenient for those standing. The use of transverse seats, as in Fig. 101, provides greater comfort for the former, but

FIG. 102.—Modified type of cross-seat car.
A development from the design shown in Fig. 101, to overcome objectionable crowding at the doors, and to permit of a wider opening.

restricts the amount of space available for the latter. The standing space is more comfortable than with longitudinal seats, since grab handles may be placed on the seat backs for support. The worst trouble is that the congestion near the entrance and exit doors is much greater than with side seats. A compromise is usually adopted in city cars by having longitudinal seats near the doors, and cross seats in the center of the car, when designed for end entrance, as in Fig. 102. With center entrance cars the

trouble is not so marked, and the seats can all be placed transversely without much danger of congestion. Other combinations may be made advantageously for particular cases.

A more logical study of both seating arrangements and door design has been made in conjunction with the prepayment of fares. The further consideration of both these topics will be taken up in that connection.

Fare Collection.—Certain roads, especially rapid transit lines, collect fares before the passengers enter the cars. This obviates any need of conductors, guards or brakemen being the only employees needed on the trains in addition to the motormen. Practically all surface roads, both city and interurban, are so situated that fares must be collected after the passengers have boarded the car. According to the older methods, the conductor passed through, collecting fares from passengers after they had entered and become seated. Often he would be in the interior doing this during a stop. This practice has two disadvantages: the conductor is not in a good position to know whether the steps are clear before signaling the motorman to start, nor can he see the passengers who are entering or leaving the car. Besides making operation dangerous, this makes fare collection difficult, and in some cases almost impossible. It also gives dishonest conductors a chance to "miss" fares, or to fail in registering them. A number of schemes to make fare collection easier and more certain, and to reduce accidents, have been tried within the past few years. Of the various ones advocated, the prepayment plan has met with the most success in the United States. It has been adopted in nearly every large city in the country, and in many of the smaller ones. The basic principle of all methods of fare prepayment is to have the conductor at or near the entrance, and to prevent any person from going into the car without first tendering his fare. By this means the conductor does not have to depend on his memory to ensure collection of fares; and he may be located in such a position that he can be sure the steps are clear before giving the signal to go ahead. In the later types of prepayment cars, various forms of doors, operated by the conductor from his fixed position, make it impossible for passengers to enter or leave after the starting signal has been given. This reduces the boarding and alighting accidents by a marked degree.

If the fares were collected at the instant of boarding the car, the time taken in loading would be materially increased. This is obviated by using the entrance platform for holding a certain number of passengers while they are getting their fares ready to present to the conductor, the door being closed and the car started immediately after they have boarded the platform. In some of the types of prepayment cars, as many as ten to twelve passengers may be accommodated in this manner, so that no more time is consumed in the ordinary stop than where fare collection is made in the old way.

Types of Prepayment Cars.—Practically any standard type of car may be arranged for fare prepayment. The success of any particular design depends to a considerable degree on the amount of space available for passengers before presenting fares. This requires special design of platforms in most cases.

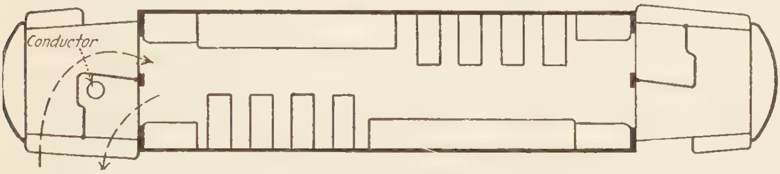


Fig. 103.—Original Pay-As-You-Enter car.

The conductor is stationed in the fixed position shown, and receives the fares from the passengers as they pass him on entering the car. The seating arrangement is not an essential feature of this type of car.

The first type of prepayment car, which was introduced in Montreal in 1905, is shown diagrammatically in Fig. 103. In this the platforms are lengthened somewhat from the standard design, and a railing divides the rear one into two portions, one for entering passengers, and the other for the conductor and leaving passengers. The conductor remains in his position at all times, and each passenger, on entering the car, tenders his fare or deposits it in a special fare box. The conductor is then in a position where he can collect all fares, and where he can watch the movements of the entering and leaving passengers. The front door is used for exit only, and is under the observation of the motorman.

In the original design, the steps were not movable, and no enclosing doors for the vestibules were provided. No special attempt was made to prevent passengers from leaving or boarding the car while in motion. Although this type considerably re-

duced the number of accidents from such causes, it did not entirely prevent them.

Another type of prepayment car, known as the "Pay-Within" car, was brought out soon after the "Pay-As-You-Enter" car, but by a rival concern. In the original form, shown in Fig. 104, the bulkheads are entirely removed, the conductor is stationed in the middle of the end entrance, and provided with an operating stand. The vestibule has sliding doors which are worked either by compressed air or by a system of hand-operated levers, worked from the operating stand. The outside steps are also arranged to fold up and disappear when the vestibule doors are closed. In this design the entire platform is made available for entering passengers waiting to pay their fares. Exit is usually made by

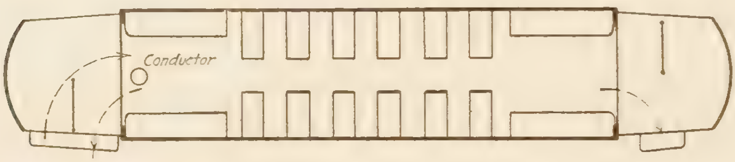


FIG. 104.—Original Pay-Within car.

A type developed soon after the P-A-Y-E car. The principal distinguishing feature is the system of doors and folding steps.

the front platform, the door being the same as that for entrance, but controlled by the motorman. With this type of car boarding and alighting accidents are practically eliminated, since the conductor is instructed not to give the starting signal until the entrance door is closed; and the motorman must not start the car, after receiving the signal, unless the exit door is closed. The distinctive feature of this car is the system of doors and folding steps.

After a few years the manufacturers of these two forms of prepayment cars combined, incorporating the good features of both. Generally speaking, the platform construction of the original P-A-Y-E car was combined with the door arrangement of the Pay-Within car, producing a design considerably in advance of either.

With cars of the prepayment type, it is essential to rapid operation that the space near the doors be as little restricted as possible. For this reason the seating arrangements have been developed from that shown in Fig. 102, since in most cities the cross seats have been found more desirable.

A further development of the door-operating principle is to have the doors arranged so that the starting signal is given automatically when all of them are closed. This may be accomplished very simply with a bell or light circuit, giving the indication to the motorman without signal from the conductor. The scheme may be carried still further, in cars equipped with multiple-unit control, by including the doors in the master control circuit. With this arrangement the car cannot be started until they have all been closed. It then becomes possible to increase the speed of operation, for as soon as the car has come to a stop and the doors have been opened, the motorman can throw his controller to the first operating position. Then, as soon as they have been closed, the car will start without signals of any sort and the motorman can at once turn his controller further as desired. If the doors are opened while the car is running, power will immediately be cut off.

Center Entrance Cars.—The prepayment principle has been extended to center side-door cars. As already mentioned, the side door has many operating advantages. It decreases the average distance the passenger must go from the entrance to find a place; and since the platforms are unnecessary, they may be entirely omitted, being replaced with seats, thus adding materially to the capacity of the car. It is also possible, by inclining the floor, to make a car with lower steps than the standard. In New York, a design has been produced in which, by having the floor inclined upward both ways from the center door, and by the use of special features, the step has been entirely eliminated, the car floor at the entrance being only 10 in. above the street level[1] (see Fig. 105).

Near-Side Car.—A special type of car has been designed for prepayment of fares in connection with the near-side stop, which is being required in many cities on account of safety. In the "Near-Side" car, Fig. 106, the entrance and exit are both on the front platform, the rear platform being entirely eliminated unless the car is designed for double-end service. The conductor is relieved of all operating duties, since the passengers enter and leave the car under the eye of the motorman. The latter, having control of both the entrance and exit doors, can start the car when he is satisfied that the steps are clear. It is possible to

[1] A complete description of this car may be found in *Electric Railway Journal*, Vol. XXXIX, p. 418, Mar. 16, 1912.

interlock the controller with the doors, so as to prevent operation of the motors unless the doors are closed. The conductor, then, acts merely as cashier, his function being to make change and assure himself that the proper fare has been deposited in the fare box by the passenger. In small cities with light traffic, the

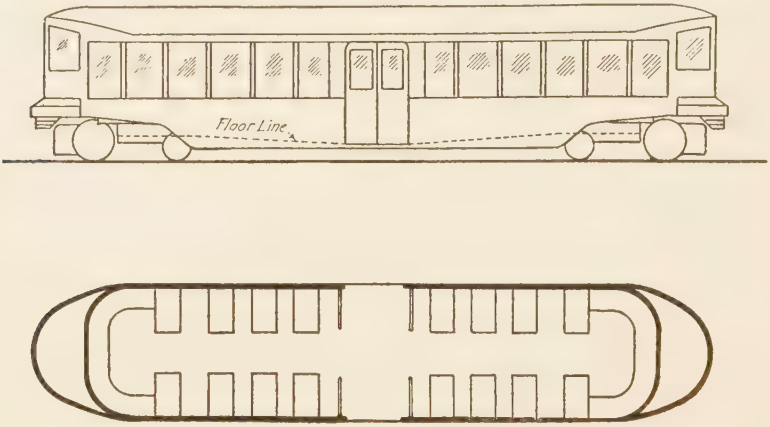


Fig. 105.—New York stepless car.

The floor level is but 10 in. above the ground, and there are no steps inside the car. Note the arrangement of seats to clear the pony wheels, and the position of the motors at the outer ends of the trucks.

conductor may even be dispensed with, the motorman performing the duties of both. In the latter case, the time consumed in stops is liable to be somewhat longer than where a conductor is employed.

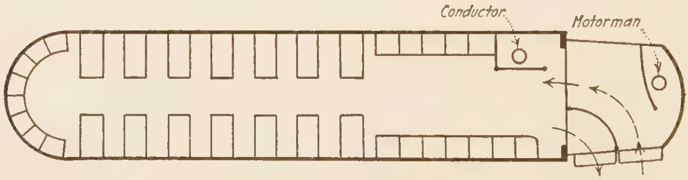


Fig. 106.—Near-side car.

The entrance and exit doors are under the control of the motorman; the conductor is not required to give starting signals.

Rapid Transit Cars.—The design of cars for service on elevated and subway roads is not limited as for use on surface lines, principally because the problem of fare collection does not enter. In all roads of this class prepayment of fares is an essential part; but, on account of the physical features, making it possible to

operate entirely on private right-of-way, payment is made in the stations before the passengers enter, so that the cars can be designed entirely for comfort and rapidity of operation. The doors of the earliest type of rapid transit car were modeled closely after those of the open platform steam coach of the same period, but the cars ordinarily had longitudinal seats instead of the cross seats of standard railroad designs. Such a car is shown diagrammatically in Fig. 107.

Fig. 107.—Early rapid-transit car.

This type, with open platforms, has been widely used on all of the earlier elevated roads. Note the position of the motorman's cab.

It is to be noted in connection with all cars for operation on elevated and subway lines that, since the platforms must be specially designed in any case, there is no advantage in having them near the level of the rail. Much more rapid loading and unloading can be obtained with them at the level of the car floor, since this obviates any need of steps. This arrangement also simplifies the car framing to some extent, since the sills can be made continuous from one end of the body to the other.

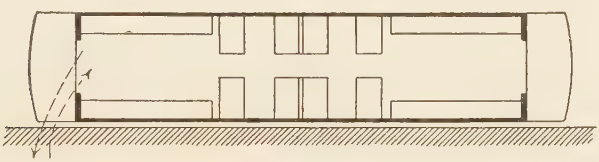


Fig. 108.—Rapid-transit car, used in New York, Chicago, Brooklyn, etc.

A modication of the open-platform car shown in Fig. 108.

Another type of rapid transit car, shown in Fig. 108, is the same in general design, but includes a few cross seats near the middle of the car. These seats are invariably of the non-reversible type. Cars such as shown in these two diagrams have been operated on the principal elevated lines for many years.

The general demand for the enclosed vestibule car led to the type shown in Fig. 109, which is the one used on several of the elevated lines of Chicago. The principal operating advantage in this design is that, since the passengers are protected from the

weather, they are better lined up at the exits when the car comes to a station.

Since the principal problem in the design of rapid transit cars is to secure swift movement of the passengers, it would appear that the addition of doors in the middle of the sides would add to

Fig. 109.—Rapid-transit enclosed vestibule car.
A later type than those shown in Figs. 107 and 108.

the speed of unloading and loading. A car of this type, shown in Fig. 110, was first used on the Boston Elevated Railroad. On that road the scheme is to have the passengers enter by the end doors and leave by the center doors. If this plan is adhered to by all the passengers, it increases the rapidity of operation con-

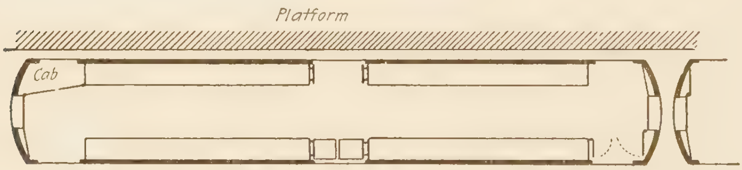


Fig. 110.—Side-entrance rapid-transit-car, New York.
A modification of the type shown in Fig. 109, to give greater facilities for rapid loading and unloading.

siderably. Unfortunately, it is not possible to completely train the American riding public to move in fixed channels, so that the advantage of establishing regular directions of movement is but partially realized. Even a partial establishment of a regular

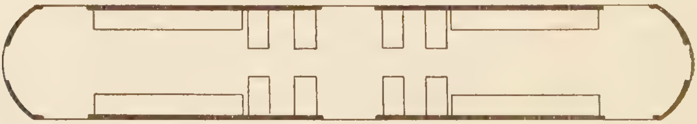


Fig. 111.—Side-entrance rapid-transit car, Philadelphia.
This differs from the New York car principally in the seating arrangement.

direction of motion helps to some extent; and it would seem that, even if no general adherence to the rule were made, the extra doors should aid in loading and unloading. Cars of a similar design have been adopted on a number of rapid transit roads.

A slight modification consists in the addition of a few cross seats on either side of the center doors, as shown in Fig. 111, which represents the type of car used on the Philadelphia elevated road.

Practically the same results in rapidity of passenger interchange should be accomplished by combining the center and end

FIG. 112.—Rapid-transit car, Metropolitan Railroad of Paris.
Note the short distance from the doors to the seats in any part of the car.

doors, placing two side doors some distance from the ends of the car, as in Fig. 112, which represents a design used in Paris. In this the maximum distance from a seat to a door is no greater than when center and end doors are used in a car of equal length.

FIG. 113.—Cambridge subway car.
A recent type of rapid-transit car, arranged for large capacity.

A movement has been growing in the past few years for longer cars for this class of service, since the passenger capacity can be increased to some extent without adding to the platform labor. Recent cars designed for the Boston-Cambridge subway (Fig. 113) and for the New York Municipal Railway (Fig. 114) are

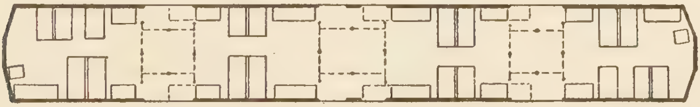


FIG. 114.—Rapid-transit car, New York Municipal Railway.
A very recent car, designed after a comprehensive study, to give maximum passenger capacity.

examples of this. In both types, the principle mentioned in the last paragraph has been used to reduce the distance from the doors to the seats; but both cars are so long (69 ft. 6½ in. and 67 ft. 4 in., respectively) that it is necessary to combine these side doors with center side doors, as used in some of the earlier designs. In

this way the distance to the seats is no more than in the end- and side-door cars; and is actually less than in much shorter end-door cars.

While it is desirable to seat every passenger, it is generally recognized that in congested business districts it is not possible to provide enough cars to furnish seats for all; and, when many business houses close at the same time, it taxes to the limit the ordinary rapid transit road to provide accommodations of any kind. This has been recognized in the car for the New York Municipal Railway. While a large door capacity is needed for rush-hour service, it is not so necessary at other times; and some of the doors are arranged to be used only when needed, folding seats being placed in front of them as desired.

The effect on operation due to the use of different rapid transit cars is very marked. For instance, it has been estimated that the new New York Municipal Railway cars will increase the capacity of the track by 20 to 25 per cent. over what it would be if the latest type of cars now in use on other roads of its class in New York City were employed; and it will also save about $200,000 a year in platform costs, and between $1,000,000 and $2,000,000 in power system capacity because of the decreased energy consumption per passenger carried.[1]

Interurban Cars.—The interior arrangement of cars for interurban roads is subject to more conflicting elements of design than in city or rapid transit service. The collection of fares must be considered to some extent, but the problem is not so serious as in city cars; for the number of passengers entering is not very large at any one stop, and the rides are longer. Further, some system of fare receipts may be used for indentification. It is more essential to provide facilities for the comfort of the passengers, and this need increases with the average length of ride. On roads operating trains for runs exceeding about two hours in length, the conveniences should be about the same as those standard for steam coaches. A car which has been adopted by one of the larger interurban roads of the Middle West is shown in Fig. 115. In this are combined the functions of standard passenger coach, smoker, and baggage car. The smoking and baggage rooms are merged, in order to save space. This compartment has a number of folding seats which are normally used for passengers, but

[1] See *Electric Railway Journal*, June 6, 1914, Vol. XLIII, p. 1261.

which can be folded back against the walls in case there is an extra amount of baggage.

The use of the center entrance car for interurban service has made but little headway so far; but it is likely to have a wider application in the future on account of its excellent qualities. The main compartment may be separated by the entrance from the smoking and baggage rooms, while the distance from any part to the doors may be reduced. Fig. 116 shows a car of this type which has been successfully used in high-speed service.

Fig. 115.—Standard interurban car, Illinois Traction System.
This car combines all the features of the ordinary steam railroad local passenger train.

A number of interurban roads have found it desirable to operate a limited freight service. To do this, motor-equipped cars of the ordinary baggage type have been used. In some cases they are operated as separate units, and in others the motor capacity is increased so that they are able to haul one or two trailers.

A demand has been found for interurban parlor-car service during the past few years; and to satisfy it, cars resembling the

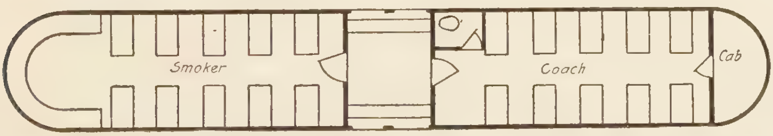


Fig. 116.—Center-entrance interurban car, Kansas City, Clay County and St. Joseph Railway.
This is a recent design, which has proved quite popular, and which has been adopted with minor modifications on a number of interurban roads.

Pullman parlor cars, but usually shorter, have been built. These are most frequently run as trailers to obviate the noise incident to motor operation, which, although slight, is objectionable to some patrons. They are usually a source of considerable revenue, for they furnish additional seating capacity which is paid for by the excess fares charged.

The demand for dining cars on electric roads has been very slight up to the present time; but in the future, if several roads

combine to give through service, it is possible that a need for them may be felt. All of the dining service now handled on interurban roads is given by buffets operated in conjunction with the parlor cars.

On a few roads it has been desirable to run night trains and to supply sleeping-car service. The cars which have been used have been specially designed, and include a number of features not seen on the standard Pullman cars. Since this service is entirely special, no attempt will be made to give detailed descriptions of the cars used.

Auxiliary Electric Devices.—Although the car body, the motors and the control are the essentials of the rolling stock, a large number of auxiliary parts are needed to complete the equipment. Principal among these are the lighting devices and heating system. While neither is used continuously throughout the operation of the car, both are necessary if the service is to be continued for more than special events.

Car Lighting.—Up to the present time, the lighting of electric cars, both for city and for interurban service, has been done by clusters of 16-c.p. carbon incandescent lamps, or by a line or lines of such lamps down the middle or sides of the car. They are placed five in series on the trolley circuit, so that standard lamps of 110 to 120 volts may be used. In order to have uniformity in illumination, and to prevent unequal deterioration, the lamps must be carefully matched to have them of the same current capacity. In most installations, the lamps have been left bare, or provided with inadequate shades and reflectors. Such a system is far from satisfactory, for the amount of light produced by the carbon lamps is insufficient for reading, while the energy consumption is high. The bare lamps are not arranged for the best distribution of the light, and they produce a glare in the eyes of the passengers which is harmful.

Within the last few years more attention has been paid to the correct lighting of cars, and illuminating engineers have put a great deal of thought on the subject. The ordinary car is a difficult interior to treat, since it is practically a long, narrow room, with but little wall space for diffusion of the light, and with a low ceiling which is usually not well designed for reflection.

The first step in the improvement of car illumination is the substitution of tungsten lamps for the carbon. By the use of 23-watt tungsten lamps in place of the 50-watt carbon lamps,

the lighting cost can be reduced to less than one-half, while the amount of light is increased about 15 per cent. This change has been made in a number of large city roads.

The change from carbon to tungsten lamps, while increasing the total amount of light, does not get rid of the objectionable glare, nor does it improve the light distribution. More recent developments have shown that by the use of fairly large units, in the neighborhood of 100 watts, spaced much further apart and equipped with proper shades and reflectors, the total amount of light in the car may be somewhat increased and its distribution made very much better. This is also accompanied by a material reduction in energy consumption for lighting, less cost of lamps, and a saving in the necessary wiring for the car. It is very probable that this method of car lighting will find more and more favor as its advantages become better known. The principal objection is that if the lighting is concentrated in five units, all in series, a failure of one lamp will throw the car in darkness. This can be taken care of by the use of a selector switch, operated by the conductor, by means of which a spare lamp may be held ready to throw into the circuit in case of another burning out. It is practically always necessary to have an auxiliary circuit for markers, destination signs, etc., and one or two lamps on this circuit can be placed in the car interior for such emergencies. In any case it is easy for the conductor to be supplied with a spare lamp, which can be used to replace one burned out.

One general objection to all lighting systems depending on trolley current is that the line potential is liable to large and sudden fluctuations. While these have but little effect on the motor operation, they cause flickering of the lights, often to such an extent as to make reading impossible. This condition is worse with carbon lamps, and is considerably improved by the substitution of tungsten lamps, particularly in large units. But there is no form of incandescent lamp which will stand a variation of 25 per cent. in potential without a wide change in candle power. Up to the present time, no remedy has been seriously suggested. One method which has been tried experimentally consists in placing in series with the lamp circuit a resistor with a large positive temperature coefficient, which will tend to steady the lamp potential. This has not been put in practical form, and in any event requires the waste of considerable energy to be effective. Another suggestion is the use of a motor-generator set for supply-

ing the lights. This is also open to the objection of being uneconomical. With trolley potentials of 1200 volts and over, it becomes a necessity to use some such device, both for supplying the lamps and furnishing current for the operation of the control circuits. This gives a partial solution of the lighting problem on such roads. On single-phase roads, the variation of the line potential is considerably less, and the lighting troubles are not so great, as on the low-potential direct-current lines.

Car Heating.—The proper heating of cars in winter is a subject of considerable importance in northern climates. The problem must be considered from a number of different angles, and is rather difficult of solution to the satisfaction of all the patrons of a road. In city surface cars, the passengers usually ride for short distances and keep on their outer clothing. It is generally sufficient to keep the cars heated to a point which will be comfortable to persons in street attire. This calls for interior temperatures of about 55° to 60° F. For suburban and interurban service, where the average ride is much longer, the passengers usually desire to remove their wraps. In this case the temperature should be from 65° to 70° F.

The proper heating of a car to the desired temperature is in itself insufficient; there must be at the same time an adequate supply of fresh air. This may be introduced by means of air ducts at the front end of the car, or by exhaust ventilators in the roof or other convenient location. In order to get the air warmed, it should be passed over the heaters for the best distribution.

For the actual generation of heat there are available at least three different systems. The simplest is the use of a small stove in each car, placed either on the front platform or in some convenient location inside. This arrangement is not very satisfactory, since it does not distribute the heat uniformly through the car. This is remedied to some extent by placing the stove on the front platform. The air is then forced over it before admission to the car. The car stove is in any case dangerous and dirty. It always requires attention, even though that may be supplied by the car crew. Its principal advantage is in cheapness of installation and operation.

A more adequate form of heating is made by the use of hot water as a circulating medium, it being heated by a small furnace located at some convenient point in the car. This gets rid of the uneven distribution of heat, and thus is better than the stove.

It is considerably more expensive to install, costs somewhat more to operate, and does not get rid of the danger and the dirt incident to the use of a coal stove on the car.

The third type of heater makes use of electric current in specially designed resistors. These may be located at convenient points in the car, usually being placed under the seats or along the side walls. The distribution of heat is about as good as in the hot-water system. The heat is clean, there is no need for attendance, and no extra fire hazard due to the use of this kind of heaters. Different degrees of heat may be obtained by subdividing the coils of the resistors as desired. It is, however, more expensive to install than the plain stove, but somewhat cheaper than hot-water heaters. The cost of operation is decidedly higher than for the other types.

On city roads the need for all of the available space for passengers, and the difficulty of the train crew finding time to care for heaters, practically precludes the use of any type of heat but electric. In this service the need for a high temperature is least, so the expense of operating electric heaters is less than for the longer runs. In some cases, electric heat may even be found cheaper on long runs than other kinds.

For interurban service, the use of electric heaters calls for a much larger expenditure of energy than on city roads. The temperature needed is greater, and the high car speed causes greater losses by convection currents and by radiation. For most interurban roads the hot-water system has proved the most satisfactory and economical of any type of heater.

Electric Heaters.—Electric heaters for car service all depend on the same principle—the dissipation of energy in resistance; and since the energy is transformed at a rate equal to I^2R, their electrical efficiency will always be 100 per cent. Mechanically, there may be considerable difference in heaters. They are usually made of resistance wire coiled on porcelain forms, and their heat storage capacity is small. Sudden variations in the trolley potential will therefore cause corresponding rapid fluctuations in the heat produced. Some forms are made with the embedded type of resistor, in which the heat capacity is much greater, and the distribution is more uniform than with the plain wire type. On the other hand, it takes a longer time to warm the car when the heat is turned on, and it does not cool so rapidly when the current is cut off.

Car Wiring.—One of the most vital, and at the same time the most vulnerable, parts of the car equipment is the main power wiring. Upon it depends the operation of the motors and their proper control. It is essential that the wiring be made in a permanent manner, so that, in spite of the rough handling and abuse incident to railway service, it will not be damaged.

The insulation of the wiring on the earliest cars was extremely crude, the wires being installed without regard to arrangement, the main idea being to operate the cars in some fashion. A few years later, when equipments had been standardized to some extent, regular cables were made up of the requisite number of wires, drawn together through a canvas hose. This method of wiring was used with considerable success for a number of years. There was always danger of abrasion of the insulation and grounding of the wires. Finally this type of car wiring was superseded by later and better methods.

A favorite method of wiring on wooden cars is to install the wiring under the car, the individual wires being insulated for the full potential and being held to the framing by separate wooden cleats. This leaves the wiring open for inspection, and separates it so well that there is but little danger of grounds and short circuits. In some cases the open construction is replaced by wiring run in metal moulding. This gives an absolute protection against mechanical injury.

For all-steel cars it is practically imperative that the wires be run in conduit. In such cases it is agreed that the best practice is to bring the wires out through standard junction boxes, and fasten them to the car underframing with asbestos board or properly treated wooden cleats, which are arranged to allow a clear space between the wires of at least 2 in.[1]

In all types of equipment, it is necessary to provide some automatic protection of the motors against overload. The ordinary method is to use fuses and circuit breakers. For the smallest equipments fuses are used alone, but their employment is open to a number of operating objections. Generally two automatic circuit breakers are placed in the circuit, one at each end of the car. In some cases these breakers are in series, while in others one is used alone at each end. For large equipments it is better to have both the circuit breaker and the fuse, the latter being set to

[1] See *Engineering Manual*, American Electric Railway Association, Section Ec 11a.

open at a slightly higher current than the breaker, so that ordinarily it will not operate.

Cars for service on overhead trolley lines should also be provided with lightning arresters and choke coils to prevent a rush of current through the motors and control in case the car is struck by lightning or a heavy surge occurs on the line.

Resistors for railway service have already been considered in connection with the control of railway motors, and with electric braking. If grid resistors of the ordinary type are used, it is essential to have them placed in such a position as will insure adequate ventilation or the operating temperature may become so high as to burn out and destroy the grids.

Collectors.—For all roads operating with overhead contact lines, some kind of collector must be used to make contact with

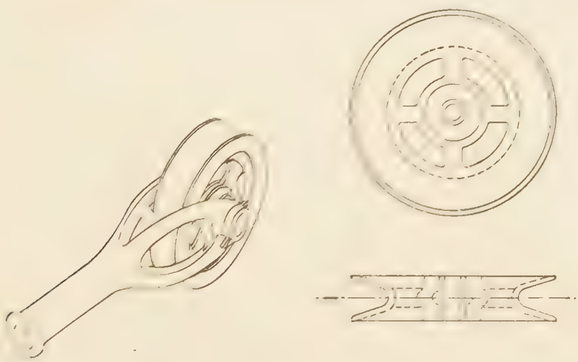


FIG. 117.—Ordinary wheel trolley.

The wheel is carried in a harp, as shown. Current is conducted from the wheel to the harp through spring brass contact pieces, bearing on the ends of the wheel axle.

the trolley wire. The usual form for low-tension direct-current roads is the common wheel trolley. This device is so well known that very little description is necessary. It consists of a swiveling base, to which is hinged a steel pole bearing at the upper end a grooved wheel of copper or bronze, as shown in Fig. 117, which runs on the lower side of the contact wire. Although this seems the obvious method of collecting current, it was not invented for several years after the operation of electric cars had become practical; and when finally developed was the subject of litigation for a long time. To keep the wheel in contact with the wire a spring is provided in the base. For low-speed roads the pressure required to maintain contact is small: but as the speed is increased

the needed pressure becomes rapidly greater. This is largely due to the uneven surface of the wire, caused by the sag between suspension points. As the car moves along the track toward a point of support, the trolley wheel gradually rises until the hanger is reached. As it is passed a rapid change in the alignment of the wire takes place, and, the wheel's upward motion being suddenly arrested, it strikes a blow on the wire. The force of the blow depends on the sag in the wire, the speed of the car, and the stiffness of the spring in the trolley base. If the spring is too stiff, a heavy blow is struck; while, on the other hand, if the pressure

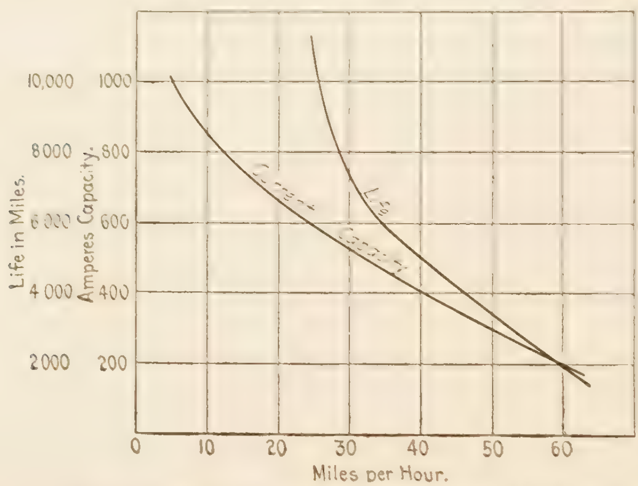


FIG. 118.—Effect of speed on current collecting capacity of wheel trolleys.

is too small, the wheel may leave the wire entirely at times. This latter condition is especially bad, since it causes a succession of arcs which pit the wire and the wheel. Pitting the wheel has the further effect of roughening the surface of the wire at other points.

These various factors cause a rapid decrease in the amount of current which a trolley wheel can collect, as the speed is raised. Although the capacity of the contact is quite large at low speeds, the current which can be successfully delivered to the car is much less when the maximum speeds reached in ordinary interurban service are attained. The relation between speed and current collecting capacity is shown in Fig. 118.

Coincident with the reduction in current capacity as the speed is increased, there is a marked diminution in the life of the trolley

wheels. The relation between the life of wheels and the maximum speeds attained is also shown in Fig. 118.

For high-speed roads, other forms of contact have been tried. Of the ones for use on overhead lines, the best are those which replace the wheel with some form of sliding contact. The two principal types of sliding collector are the bow trolley and the pantograph. Their successful operation depends to a large ex-

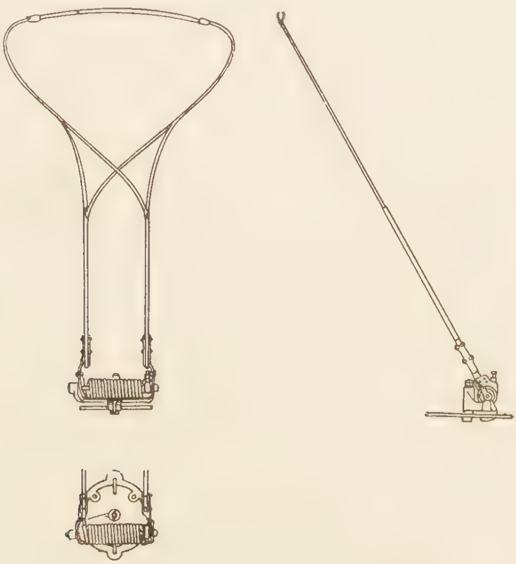


Fig. 119.—Bow trolley.

This design is better suited than the wheel trolley for current collection at high speeds, on account of its smaller inertia. It is widely used in Europe.

tent on making a structure of such light weight and small inertia that heavy blows will not be delivered to the wire as the car passes beneath. At the same time it has become customary to use a form of construction in which the trolley wire is held more nearly in a horizontal plane.[1]

The bow contact is made in two entirely different forms. The bow trolley proper, Fig. 119, replaces the trolley pole and heavy wheel with a light framework supporting a horizontal contact piece of steel or aluminum, which is held against the wire by means of a spring, or, in high-potential equipments, by a compressed air cylinder. With the latter arrangement it is unneces-

[1] See Chapter XII, "Catenary Suspension."

FIG. 120.—Pantograph trolley.
This type is in use for current collection in fast, heavy service, such as on trunk lines.

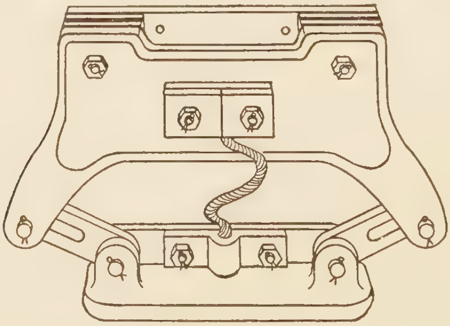


FIG. 121.—Over-running third rail shoe.
This type is in use on practically all the elevated roads of the country. It is only suited to the unprotected top-contact rail.

sary for the operator to come in contact with the live portion of the circuit in any way, since the air may be applied by remote control, usually being worked by the motorman from a connection on the master controller.

The pantograph trolley, Fig. 120, consists of a light diamond-shaped framework carrying at its top the contact piece, which is similar in form to that used with the bow trolley. This type is almost invariably operated by compressed air.

On third-rail roads, a special form of collector must be used. Since the rail is carefully aligned with the track, there is no variation in level, and the need of a heavy spring to insure contact is unnecessary. For over-running[1] rails a very simple type of collector may be employed. One of the commonly used forms is shown in Fig. 121. It consists of a loosely jointed pantograph of

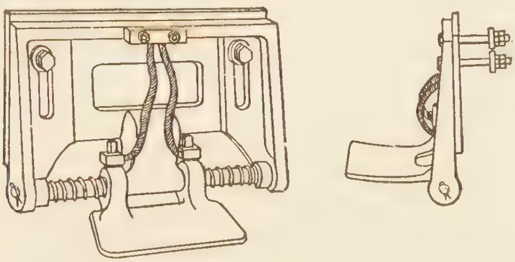


FIG. 122.—Slipper shoe for under-running third rail.
This type is standard for bottom-contact rails, or for protected top-contact rails.

small dimensions, carrying at the bottom a contact shoe which is held on the rail by gravity or by a light spring. Connection is made to the car wiring by a flexible cable. When the under-running third rail is used, a different form of shoe is employed, a common type being shown in Fig. 122. This shoe, known as the "slipper type," has a hinged contact piece carried from a light framework attached to the truck. Its action is obvious from the diagram. This shoe is also excellent for over-running rails; and it is possible to arrange it so that it may be used interchangeably for either top or bottom contact.

Car Painting.—No matter what the materials of which the car is built, it is necessary to provide some sort of protective coating, usually paint for the outside, and varnish for the interior over the natural wood. The proper finishing of cars is a subject which has

[1] See Chapter XII, "Over-running Third Rail."

received less attention than it merits, for on it depends to a considerable extent the life and general appearance of the equipment, whether the material be wood or steel. A description of the methods employed is out of place in this book, but may be found by reference to the files of the railway periodicals.

Miscellaneous Details of Car Equipment.—In addition to the apparatus already considered, there are many minor parts of the car equipment which are essential to successful operation. Seats, curtains, ventilators, door-operating mechanism, destination and route signs, headlights, markers, and a number of other parts are all necessary to make the equipment complete. While a detailed discussion of these parts of the car is unwarranted, it must not be forgotten that there is more or less latitude in their selection, and

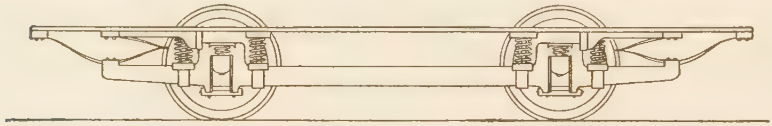


Fig. 123.—Single truck, 7-ft. wheel base.

Trucks of this and similar types are in use on practically all of the single-truck cars in operation.

that considerable care should be taken to obtain proper and satisfactory material.

Trucks and Running Gear.—The operation of railway vehicles makes necessary some adequate form of running gear, which will carry the body in such a manner as to prevent objectionable shocks and vibration. The method of support differs widely, the principal variation depending on whether the car is mounted on a single rigid framework, or has two swiveling trucks.

Single Truck Cars.—The smaller cars for city service, having bodies not more than about 20 ft. long, can be carried with satisfaction on a single rigid-frame truck. The construction is of the simplest character, consisting of a support for the car body and pedestal bearings for the axles. In general, a rigid mounting of the car on the truck is undesirable, so that some form of spring is interposed; and the truck proper is supported on the journals by helical springs over the pedestals or by an arrangement of elliptical or semi-elliptical springs. The single trucks produced by different manufacturers vary widely in their details, but all are quite similar in general appearance. A typical single truck is shown in Fig. 123.

When the car body is too long, difficulties arise in the design of single trucks. In order to operate satisfactorily on city track, where the curves are almost invariably of short radius, the rigid wheel base must be kept to a minimum length, or binding of the flanges, and in some cases more serious trouble, will result. If the wheel base is short, there will be a large overhang

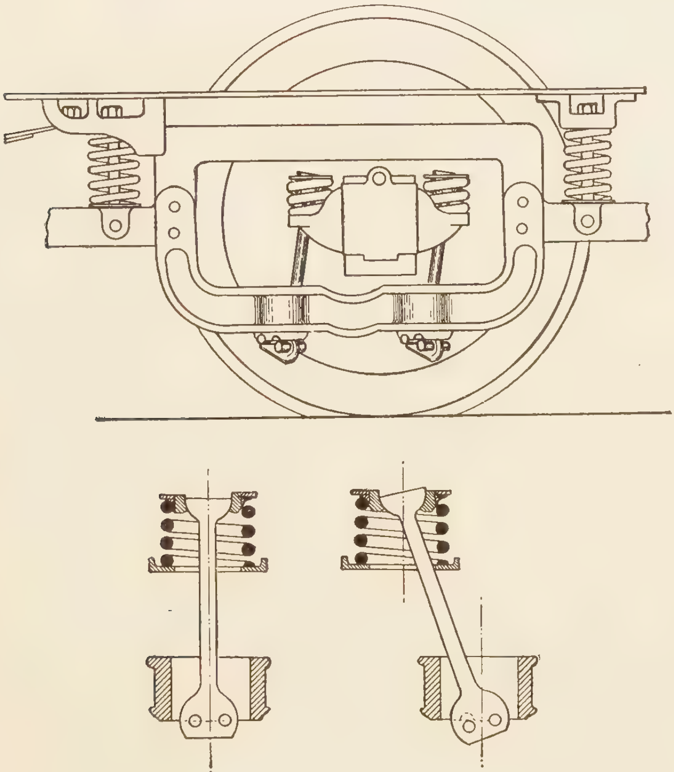


Fig. 124.—Brill radial axle truck.

Note the action of the hangers. By this means a longer wheel base can be used on a single-truck car than is possible with the design shown in Fig. 123.

at the ends of the car, giving a weak structure, and causing longitudinal oscillations if the car is operated at high speeds. The ordinary methods of spring mounting of the body do not remove this difficulty, but at certain speeds may aggravate it. The simplest solution is to use two swiveling trucks under the car; but this increases the expense, and may appear undesirable if the car is only slightly above the limiting length. Another solution which

has been developed is to carry the axles on hangers which may be swung at an angle with the car body when rounding curves. With proper design, the hangers can provide for throwing the axles in a radial direction as the curve is reached, restoring them to the parallel relation after getting back on tangent track. One form of hanger and the method of operation are shown in Fig. 124.

Swiveling Trucks.—For long cars, and for some locomotive service, it is necessary to use two swiveling trucks to provide for operation around curves. The trucks are independent structures, and are each connected to the car body by a single heavy pin, or "king-bolt." They are then free to turn, and allow the wheels to align themselves on any track. This construction is applicable to cars of any length. In order to prevent dangerous swaying of the car body, it is customary to provide bearings at the

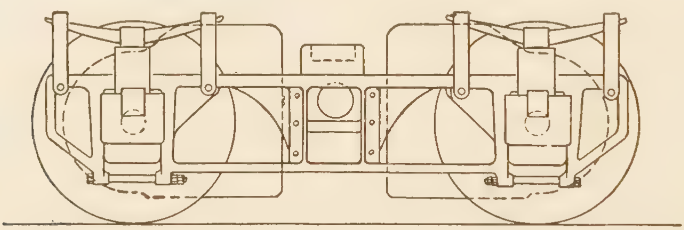


Fig. 125.—Rigid bolster truck.
Suitable for slow-speed locomotive service only.

sides of the truck to limit the oscillation of the car at high speeds. These may be either flat plates or ball bearings. For the latter it is claimed that the friction is reduced materially, since the trucks are more free to align themselves with the track.

The principal differences in trucks are in the methods by which the car body is hung. The simplest way is to support the bolster rigidly from the truck frame. The only spring possible is then that over the pedestal. Trucks of this type, as shown in Fig. 125, are only suitable for slow-speed locomotive service, the cushioning being insufficient even for freight cars.

The floating bolster construction, shown in Fig. 126, detaches the bolster from the rigid connection with the side frames, and supports it through elliptical springs acting in a vertical plane transverse to the direction of motion of the truck, the bolster being allowed to move in ways provided for that purpose. While

the cushioning is better than with the rigid bolster construction, it is not sufficient for high-speed passenger operation, but is chiefly confined to freight-car and locomotive service.

A further development is the swinging bolster truck. In this type the bolster is mounted on springs traveling in a guide, as with the floating bolster; but the springs, instead of resting directly on the side frames, are carried by a saddle or series of hang-

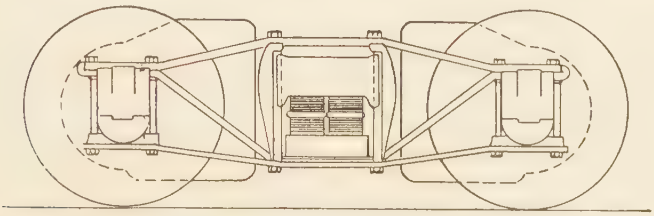


Fig. 126.—Floating bolster (arch bar) truck.
Suitable for freight cars, but not flexible enough for passenger cars.

ers which allow the bolster to swing in a transverse direction. This permits the car body to roll or sway on curves and at high speeds, reducing the shock to a minimum. Trucks of this kind are standard for all steam and electric railway passenger cars, and are built in a multitude of forms for every class of service. A widely used type is shown in Fig. 127.

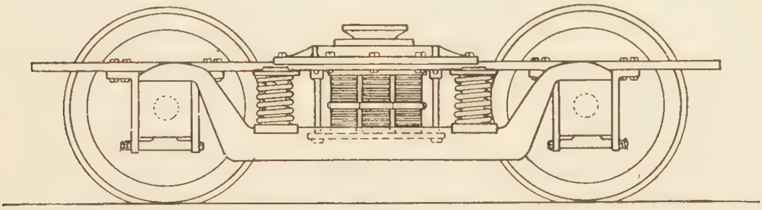


Fig. 127.—Swinging bolster truck.
Suitable for high-speed passenger cars. Trucks of this general type are made in a wide range of forms.

Maximum Traction Trucks.—It has been shown that it is desirable to use a minimum number of motors consistent with obtaining the necessary tractive effort for car operation. For city service this generally calls for two motors per car. If the car body is too long for a single truck, ordinary swiveling types can be used; and the motors may either be mounted both on one truck, the other being without electrical equipment, or one may be

mounted on each. When the cars are to be operated in either direction the latter method of mounting is preferable, since the weight transfer between the trucks is then equalized for both directions of motion. In cases where the acceleration demanded is high, the use of two motors may not give sufficient adhesion, since only about 60 per cent. of the total weight is carried on the motor-equipped axles (a portion of the motor weight is carried directly, accounting for the increase over the 50 per cent. which might be expected). The weight distribution may be changed to throw a greater portion on the driving wheels by placing the bolster nearer the driving axle. In this way the available adhesion may be increased to between 70 per cent. and 85 per cent. of the total car weight. Since the trailer wheels are not carrying

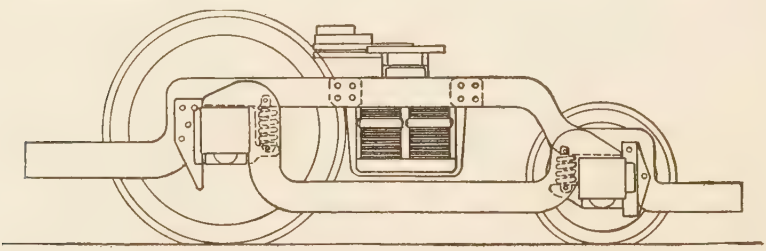


FIG. 128.—Maximum traction truck.
Used for city cars, in order to employ two-motor equipments with high accelerations.

as much weight as the others, their size may be considerably reduced without difficulty, and without affecting the riding qualities. In this form the "maximum traction" truck has been standardized, and is used on a number of roads. One style is shown in Fig. 128. A feature of trucks of this class is that the small wheels may be allowed to extend under the drop platforms of city cars, thus increasing the total wheel base beyond what would be possible with standard trucks. This tends to make the car easy riding.

All maximum traction trucks are subject to one objection. Since a large portion of the total weight has been transferred to the driving wheels, there may not be enough weight on the small ones to keep them on the rails at sharp curves, especially at high speeds. For this reason maximum traction trucks are considered unsafe at speeds over about 30 miles per hr. If higher speeds are desired, standard trucks should be used, and the acceleration kept down to a point where there will be no danger of

exceeding the adhesion; or, if the high accelerations are necessary, four-motor equipments should be used.

Motor Suspensions.—In adapting trucks for electric operation, it is essential to make provision for mounting the motors on them. It has become the universal practice to gear the motors directly to the axles without intermediate flexible connections, so that it is necessary to maintain the gear centers at a constant dis-

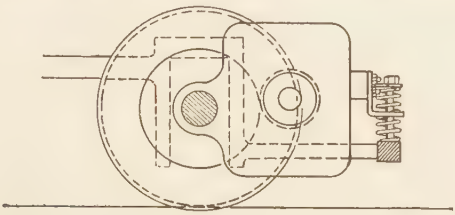


FIG. 129.—Nose suspension (outside hung motor).

This method of support makes it possible to carry a portion of the motor weight on springs. There are several variations from this arrangement.

tance to ensure their correct operation. This practically means that a portion of the motor weight must be carried directly on the axle. Generally, bearings are provided on the motor case, to give the necessary support for the machine and for the purpose of aligning the gears. The remainder of the motor weight may be spring borne by any available means.

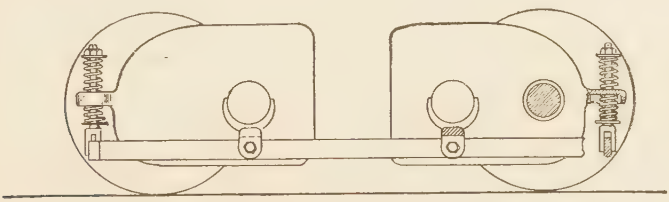


FIG. 130.—Gibbs cradle suspension.

With this arrangement, the motors mutually support each other. Used for heavy equipments.

The simplest and oldest arrangement consists in using a lug or nose cast directly on the side of the motor case opposite the axle bearings, and which is connected to the side frames of the truck by a transverse bar, the support being through helical springs. A number of variations in this form of construction may be made. One standard type of mounting is shown in Fig. 129.

Another method of spring support consists in the use of a cradle in which the two motors are hung. This allows them to mutually

carry each other through springs. A suspension of this type is shown in Fig. 130.

The motors may be placed either between the axles of the truck or outside. In general, it is better to place them inside, since this decreases the over all length of the truck and gives better weight distribution while accelerating; but in some cases the wheel base required is so short that there is not sufficient room for the motors. It is then necessary to place one or both motors outside of the axles. The mounting of a motor in this way is shown in Fig. 129. This construction is ordinarily used with the nose suspension, and is adopted only for light trucks, since long, heavy cars are not well suited for operation around curves of extremely short radius.

Motor Gearing.—Ever since the direct form of drive has been used for railway motors, it has been the custom to use high speeds for the motor armatures with considerably lower axle speeds. This reduces the weight of the motor for a given output, and permits a more efficient construction. The early motors were designed for extremely high speeds, 1000 to 1500 r.p.m. being about the range employed. Since the axles of street cars with 30-in. wheels rotate at 100 to 200 r.p.m., it follows that the speed ratio is in the nature of 10 : 1. The space limitations make the greatest practical ratio for railway service with a pair of spur gears about 3½ : 1, so that these high motor speeds call for a double reduction. After a few years' experience with this arrangement, it was found better to reduce the motor speeds somewhat, so that a single pair of gears could be used. The present street railway motors have armature speeds of from 500 to 750 r.p.m., making a single reduction entirely practical.

The early gears were of cast iron or malleable iron, and the pinions of rawhide or soft steel. After a comparatively short trial, it was found that rawhide could not stand the severe service demanded, and steel was employed exclusively. The use of steel pinions with cast-iron gears caused the most of the wear to fall on the latter; and to prevent rapid destruction malleable iron was substituted for cast iron. This material was more economical, but it was soon found that a better gear could be made of cast steel, with greater strength and longer life than from malleable iron.

Although cast steel has given considerable satisfaction, it has not proved uniform enough in quality to allow of its

being worked up to its limit of strength. More recent designs of gears have been made of forged or rolled steel, which has at once greater uniformity of composition and a chance for varying the ingredients to meet the needs of a particular service. Harder steels have been used; but it has been found that with the hard steels there is more tendency to brittleness, which may cause the teeth to break before their limit of wear is reached. To obviate this difficulty two methods have been employed. In the first the gears have been made of a low-carbon steel which is tough. After the teeth are cut the gear is treated to a case-hardening process, giving a surface which is flinty and wear-resisting, while the interior remains fibrous and tough. The other method is to make the gears of a metal which will allow surface tempering. This requires a steel which is somewhat higher in carbon, but it is claimed that the heat treatment leaves a hard wearing surface with a tough core. Both types of gear are in common use now, and are giving greatly increased life—in many cases equaling the life of the axle itself. The increased life with the improved forms of gearing is from three to five times that with the cast-steel gear and machinery-steel pinion, while the cost is from one and one-half to two times as great. In figures, the life has been increased from about 100,000 miles for a cast-steel gear, to 350,000 miles for a tempered one and 500,000 miles when case-hardened.

While the wear on gears is severe, that on pinions is still worse, since the number of teeth is smaller. Some of the pinions are made of case-hardened steel, and others of heat-treated steel. A recent development is the use of tempered tool steel for pinions. It must not be overlooked, however, that a great increase in hardness of one of the meshing gears above that of the other may cause wear of the softer metal.

The early gears were cast in halves, and held on the axle with bolts. This construction makes it easy to replace damaged gears, but results in a structural weakness, with corresponding liability to breakage. With the later high-grade gears, lasting about as long as the axles, the need for having them split for easy removal has disappeared, so that it is preferable to make them solid and press them permanently on the axles.

To lengthen the life of the gearing, it is always enclosed in a special dust-proof case. The cases supplied by the manufacturers are ordinarily of malleable iron, but in some instances

they are made of pieces of sheet steel riveted or welded together. Since the principal function of the case is to protect the gears from dirt and it does not carry any other parts, its mechanical strength is of secondary importance. The bottom of the case comes within a few inches of the top of the rail; and if there is not sufficient strength there, it may be crushed or broken when obstructions are encountered projecting above the level of the rails.

An important point is the width of face and the thickness of tooth. It is on these factors that the size of gearing is determined. Since the space available for the motor is limited to the distance btween the wheel hubs, less that taken by the gears, it is imperatve that the width of face be kept a minimum. Since the only other dimension which is capable of change is the thickness of tooth, the pitch must be kept a maximum. This has resulted in diametral pitches of 2½ to 3, which are common for motor gearing. Once this value has been fixed, the total number of teeth which can be placed on the gear and pinion is determined by the distance between centers. When a motor is designed, it is necessary, in order to prevent extra cost of patterns and special machining, to keep the axle centered at a fixed distance from the armature shaft for all motors with the same frame. Since the force exerted at the pitch line is approximately constant for all gear ratios, the diametral pitch should be kept uniform for all changes in speed of the motor. The various possibilities for speed reduction lie in the gears whose teeth total the same. For example, if a certain motor is designed for a normal gear reduction of 20:59, the only allowable changes from this are such as will give the same total of 79 teeth on the gear and the pinion. Possible ratios are then 22:57; 21:58; 19:60, and so on; and in all these combinations the strength of tooth will be constant.

The limits in gear reduction are, on the one hand, the minimum diameter of pinion or the maximum size of gear that can be used; and on the other, the dimensions of the gear case which can be employed. The smallest number of teeth which can be used on a pinion without undercutting the teeth to a point where they are materially weakened varies with the form of tooth, but will generally be about 12 to 15. This gives an absolute minimum size to the pinion, and a limit to the reduction in speed. The gear, on the other hand, must not be so large that there will be no clearance beneath it, or there will be danger of the gear case

striking the track. This limit is a real one, for the ordinary minimum clearance beneath the gear case is only 3 to 4 in. The other limit is seldom reached, for the maximum-speed equipments are not nearly so much in demand, and a very low reduction can be made without encroaching on the clearance limits.

CHAPTER IX

ELECTRIC LOCOMOTIVES

Development.—The early experimental applications of electric power to traction all contemplated the use of locomotives. This was undoubtedly due largely to the example set by the steam locomotive, which was at that time the accepted motive power for all classes of railways, except street-car lines. When the possibilities of the electric motor were better known, it was seen that superior results could be obtained by placing the entire equipment on the cars, thus eliminating the unnecessary dead weight incident to locomotive operation. This arrangement has become standard for all street cars, and for rapid-transit lines, so that there is no field for the electric locomotive in these classes of service.

Advantages of Motor Car Trains.—For such roads as those mentioned above, there are several advantages to the use of motor cars, which cannot be obtained when locomotives are employed. Where exceedingly high acceleration is a prime requisite, the drawbar pull of a locomotive would be so great as to make it a practical impossibility. For instance, the express trains in the New York subway, consisting of seven motor cars and three trail cars, weigh approximately 360 tons. These trains are accelerated at a rate of 1.4 miles per hr. per sec. up to a speed of about 20 miles per hr., the maximum running speed being in the neighborhood of 40 miles per hr. This service calls for a tractive effort at starting, on straight level track, of approximately 53,000 lb., which must be maintained up to about 20 miles per hr.; at the maximum speed the tractive effort is roughly 4400 lb. While the drawbar pull at starting is approximately that of a consolidation locomotive of standard steam railroad design, there are none in service which can maintain it up to the high speed required.

Another advantage of the motor-car train is its extreme flexibility, when operated with multiple-unit control. The number of cars may be adjusted to suit the traffic, since each can be made an independent unit. The motor equipment is just sufficient

to give the desired tractive effort, so that there is no question of underloading or overloading, as often happens with locomotives.

Field of the Electric Locomotive.—When cost is considered, motor cars do not compare so favorably with locomotives; for the large number of comparatively small motors, with their complicated wiring and control, will usually cost considerably more than when the same power is concentrated in a few locomotive units. The flexibility due to multiple-unit control can be obtained to some degree with the latter, for these can be built in sizes of, say, one-half the normal capacity. Such units can be operated singly or in groups, so as to give approximately the correct power for any train in use.

The example cited above is one in which the locomotive could not be used to advantage. This is generally the case where the service is severe, and the acceleration is high. But where the schedule does not call for so great tractive effort, the obvious advantage of the locomotive may make it desirable instead of the motor-car train. Such operation is that of trunk line through trains in ordinary passenger service, and, in general, of all freight trains. Although the use of individual motor cars for freight service has been proposed, there is no doubt but that any electrification involving the haulage of large amounts of freight will call for locomotives, operated as single units or in groups. It is in such service that the electric locomotive has its field.

As compared with the steam, the electric locomotive possesses the great advantage of capacity. Since the boiler, with its weight of water, and the tender, with a considerable load, are absent, the entire equipment may if desired be used for adhesion. The locomotive being essentially a pulling machine, any weight which is not used for adhesion is a dead loss; and this weight should be kept a minimum.

It must be remembered that while the steam locomotive is complete in itself, the electric engine is but one part of the electric power system. While the output of the former is limited to what it can develop, the latter has behind it a source of power which is much greater; so that the electric locomotive can carry overloads for a short period which would be quite beyond the capacity of the engine and boiler of the ordinary steam locomotive.

Due to the inherent characteristics of electric motors, the locomotive is better adapted to haul trains at high speeds when

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developing maximum tractive effort, than is the steam locomotive. For this reason it has the ability to pull large loads at considerably higher speeds, which tends to increase the capacity of the track. The possibility of subdivision makes the proper selection of units easy to give the best combination for any class of service.

On account of the power-plant apparatus being concentrated, the stand-by losses incident to steam operation are largely eliminated. In a system of moderate size the average load at any period of the day can be made fairly constant, so that the boilers and generating equipment are loaded near their maximum capacity; and the losses due to coal consumption while locomotives are ready for service, but not actually in use, are very small. There is no need for long periods of rest, such as those due to cleaning out flues, washing boilers, and other incidents to steam operation; nor is there the waste of fuel in starting fires at the beginning, and dumping them at the end of the run. These characteristics materially increase the amount of time the locomotive can be in service, so that the total number of units required is less than for steam traction.

Wheel Classification.—There are two methods of notation in use for representing the arrangement of wheels on locomotives. The method most used in America is to give the *numbers of wheels*, first for the leading truck, then for the drivers, and finally for the trailers. A locomotive of the familiar "American" type is shown by the symbol 4–4–0, there being a four-wheeled leading truck, four driving wheels, and no trailers. In the European classification system the *numbers of axles* are referred to, the leading and trailing wheels by number, and the driving wheels by letter, *A* being equivalent to a single axle, and so on. Thus the American type engine would be represented in the European notation as 2–*B*–0. Since this method of designation is so much more expressive, differentiating between driving and idle axles, it will be used in this chapter.

The table on page 243 shows the classification of standard American steam locomotives.

While the wheel arrangements of electric locomotives differ somewhat from those given for steam engines, the latter are useful for reference and comparison.

Classification of Steam Locomotives

Name	Wheel arrangement	Classification		Per cent. weight on drivers	Service
		American	European		
Single driver	∠oo⊙o	4–2–2	2–*A*–1	45	Light passenger (obsolete).
American	∠oo⊙O	4–4–0	2–*B*–0	65	Light passenger.
Columbia	∠oO⊙o	2–4–2	1–*B*–1	65	Light passenger (obsolete).
Atlantic	∠ooO⊙o	4–4–2	2–*B*–1	55	High-speed passenger.
Forney[1]	∠ O⊙oo	0–4–4	0–*B*–2	50–65	Suburban (obsolescent).
Switcher[1]	∠ O⊙O	0–6–0	0–*C*–0	100	Switching and helper.
Mogul	∠oO⊙O	2–6–0	1–*C*–0	86	Light freight (obsolescent).
Ten-wheel	∠ooO⊙O	4–6–0	2–*C*–0	75	Passenger and freight.
Prairie	∠oO⊙Oo	2–6–2	1–*C*–1	75	Heavy passenger and freight.
Pacific	∠ooO⊙Oo	4–6–2	2–*C*–1	60	Fast, heavy passenger.
Consolidation	∠oOO⊙O	2–8–0	1–*D*–0	88	Freight.
Mastodon	∠ooOO⊙O	4–8–0	2–*D*–0	80	Freight.
Mikado	∠oOO⊙Oo	2–8–2	1–*D*–1	75	Heavy freight.
Mountain	∠ooOO⊙Oo	4–8–2	2–*D*–1	70	Very heavy passenger.
Decapod	∠oOO⊙OO	2–10–0	1–*E*–0	90	Heavy freight.
Santa Fe	∠oOO⊙OOo	2–10–2	1–*E*–1	80	Heavy freight.
Mallet[1]	∠oO⊙O-O⊙Oo	2–6–6–2	1–*C*+*C*–1	85–100	Mountain service.

Electric Locomotive Types.—The early electric locomotives were nearly all direct adaptations of motor cars, the motor capacity being increased so that one or more trailers could be hauled by a car, usually of the baggage type. This practice developed until it was found that the equipment could be more advantageously disposed by limiting the duty of the motor vehicle to pulling only. This led to considerable variation in the design of the superstructure; but the fundamental part, the trucks and running gear, remained the same as in ordinary double-truck cars. Since the object is to develop the greatest possible tractive effort with

[1] The wheel arrangements of locomotives under these same names vary somewhat. Those given are typical.

the available weight, such locomotives are invariably equipped with four motors. The general arrangement is shown in Fig. 131. The motors are of the ordinary type, with single reduction gears. It is also possible to use gearless motors on this type of locomo-

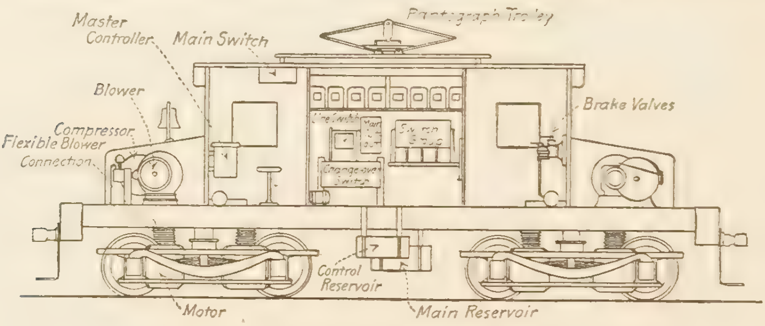

Fig. 131.—B+B geared locomotive, Southern Pacific.
Locomotives of this general type are in use on many interurban railroads. Note the compact arrangement of the equipment.

tive, but the advantage is small and the weight and cost considerably greater for the same output. It is mechanically well suited for slow operation; but when run at high speeds, the weight supported directly on the axles without springs is so great as to cause pounding of the track.

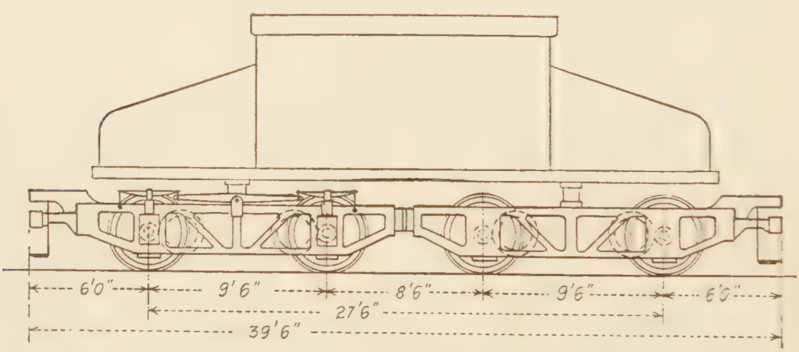

Fig. 132.—O–B–B–O geared locomotive, Baltimore and Ohio.
This locomotive is well suited for slow-speed, heavy freight service.

It is evident that the entire draw-bar pull of the swiveling-truck locomotive must be transmitted through the center plates. This renders the design unsuitable for heavy loads, and a modification has been made by articulating the trucks together and mounting the draft gear directly on them, as shown in Fig. 132.

The cab is light in construction, and serves principally to house the control apparatus.

Locomotives of the above types can be modified for high-speed operation by the addition of leading and trailing wheels, which serve to guide the heavy rigid structure, and prevent "nosing,"

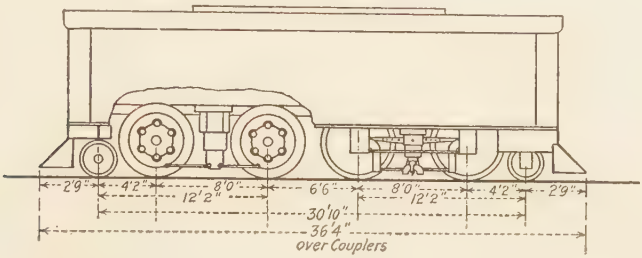

Fig. 133.—1–B+B–1 gearless locomotive New York, New Haven and Hartford.

This design has proved excellent for high-speed, heavy passenger trains in trunk-line service.

especially on curves. A locomotive of this type is shown in Fig. 133. This represents a gearless locomotive built for the New York, New Haven and Hartford single-phase line. A somewhat similar design, in service on the New York Central, is shown in Fig 134. In this design a four-wheeled leading and a similar trailing truck are used.

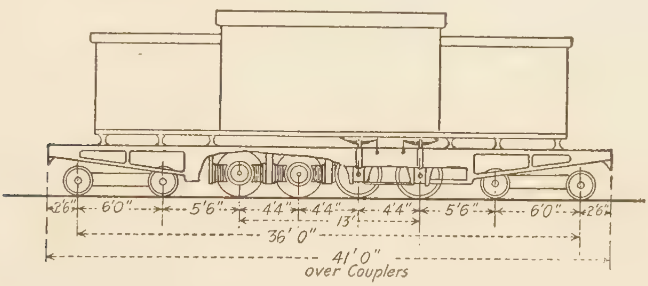

Fig. 134.—2–D–2 gearless locomotive, New York Central.

This type has been used for heavy terminal passenger service. The dead weight on the axles is rather large for successful operation at high speeds.

For heavy service, especially at high speed, the above types have not proved entirely satisfactory. Many attempts have been made to improve the transmission by the use of cranks and side rods. These designs have been employed to a considerable extent in Europe, and to a much smaller degree in America. The

most successful one in the United States is that of the Pennsylvania Railroad, for service at its New York terminal. This engine is shown in Fig. 135. The motors are spring-supported on the running gear, and are connected to jackshafts which in turn drive the wheels through parallel rods.

When the motor speed is too high for direct connection, the motor may be geared to a jackshaft. A locomotive of this class

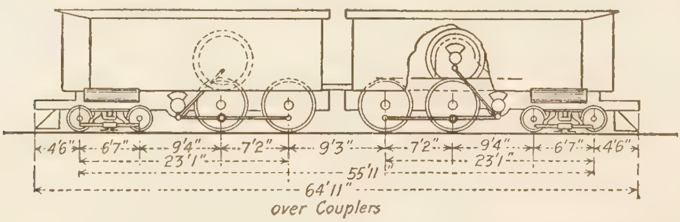

Fig. 135.—2–B+B–2 gearless locomotive, Pennsylvania Railroad.
A high-speed passenger locomotive, with crand and side rod drive. Note that the motors are mounted high above the driving wheels, raising the center of gravity.

is shown in Fig. 136. This represents the latest design used on the Lötschberg Railway in Switzerland. Flexibility is accomplished by connecting the motors to the driving wheels through "Scotch yokes," which permit a certain amount of vertical movement, while there is no horizontal play save that required for the bearings.

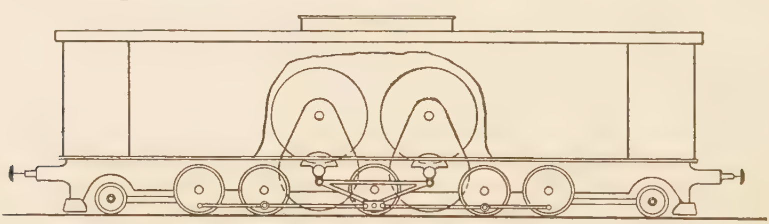

Fig. 136.—1–E–1 geared locomotive, Swiss Federal Railways.
In this design the necessary play between the cranks and the side-rods is obtained by the use of "Scotch yokes."

Application of Locomotive Types.—For slow-speed service, such as freight and switching, the principal requirement is to get the maximum tractive effort from the available weight. For this purpose the entire mass should be mounted on the drivers, leading to the swiveling truck or articulated types, such as are shown in Fig. 131 and Fig. 132. These designs have proved entirely satisfactory in service of this kind.

For fast operation, it appears almost essential to place a portion of the total weight on leading trucks, in order that the main mass may be guided along the track. In addition, there seems to be ground for believing that the center of gravity of the locomotive should be made as high as possible. When the mass is low, there is little cushioning of the oscillations as the locomotive moves from side to side of the track, due to irregularities in the alignment of the rails. The parts rigidly mounted on the axles are especially destructive in their action. The result is excessive maintenance costs; and, since the force of the blow depends on the kinetic energy of the moving parts, the effect increases as the square of the speed. On the contrary, if the mass of the locomotive is high above the track, the result of variations in the alignment is to cause the superstructure to sway, while the wheels follow the small irregularities of the rails. The locomotive is not so easy riding; but, since its function is to develop tractive effort, this does not cause any operating difficulty, while the wear on the track is reduced. For this reason, designs of the general form shown in Figs. 135 and 136 have been developed for high-speed passenger service.

In general, to secure a high center of gravity, it is necessary to place the motors on the superstructure of the locomotive, which causes difficulty in making a mechanical connection with the driving wheels. This inevitably leads to a design embodying cranks and side rods. One of the early arguments made in favor of electric locomotives as compared with steam was the absence of reciprocating parts; and it now appears that it may be impossible to eliminate them from electric engines. The effect of the rods is, however, not so destructive in the latter case, for the motor has a rotary motion, giving uniform torque at all points in the revolution. In order to transmit the motion without severe twisting strains, it is essential that cranks be placed on both ends of the armature shaft. By placing them 90° apart, the torque will be transmitted uniformly at any position; for the action is comparable to the addition of two sine waves in quadrature, as in a two-phase electric circuit. The sum of the two is always a constant quantity. On account of this uniformity in turning effort, the strains on the track are not so severe as in steam practice, and the wear on the reciprocating parts is less.

A mechanical difficulty is introduced by the crank and side-rod construction which does not exist in steam locomotives. Both

cranks are attached to the same armature shaft and driving wheels. If the parts are not in perfect alignment, the torsional strains in the shafts and connecting rods will be great. In some cases they have been so severe as to shear off the cranks or to break the shafts, while in others the bearings have excessive wear. The obvious remedy is extreme accuracy in alignment of the cranks and bearings; but this calls for careful maintenance, which cannot always be obtained in the ordinary railroad repair shop.

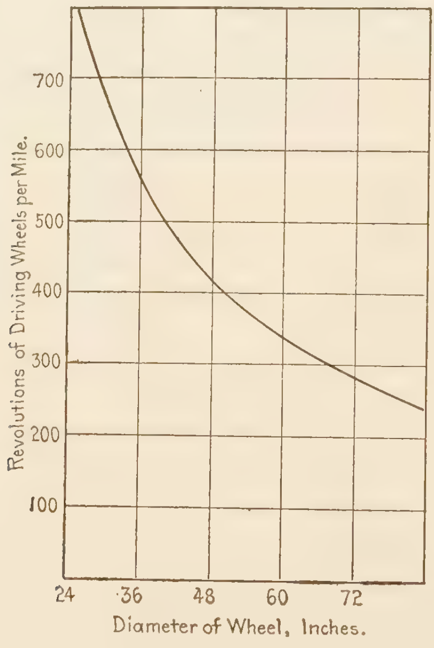

FIG. 137.—Revolutions of driving wheels per mile.

Geared and Gearless Motors.—The proper speed of the motor armature and of the driving wheels has an important bearing on the design of the mechanical transmission in the locomotive. The electric motor is, in general, essentially a high-speed machine. If it is to be directly connected to the drivers the wheel diameter should be chosen to give the proper armature speed for economical operation. In locomotives for fast service, this is not very difficult. The relation between the diameter of drivers and the revolutions per mile is shown in Fig. 137. At a speed of 60 miles per hr., the revolutions per mile and per minute will be the same.

With 44-in. drivers, as are used on the New York Central gearless locomotives, the armature revolves at 460 r.p.m. at this train speed. This is a fair value for motors of the size used. Even with 72-in. drivers, as on the Pennsylvania locomotives, the speed is 280 r.p.m., which is not excessively low, since the entire locomotive capacity is concentrated in two machines. But if similar gearless locomotives were to be used for normal speeds of 20 to 30 miles per hr., the armature speeds would be so low as to be electrically inefficient, and the weight would be excessive for the output.

It is apparent that if the normal speeds are to be low, the wheel diameter must be reduced for a gearless locomotive. If the motors are mounted directly on the axles, this will probably be impossible, since the armature diameter with the high-speed motors is so large that there is little excess clearance above the track. For motors driven through cranks, the wheel size may be reduced somewhat; but since one of the advantages to be obtained by crank connection is the raising of the center of mass, this will lead to an awkward design. The difficulty can be overcome by gearing the motors, for then the motor speed may be chosen to give good efficiency, while the wheel diameter may be such as demanded by the operating characteristics. There are many reasons why large drivers are to be preferred. They give more surface of contact between wheel and rail, with consequently greater adhesion. The shocks while climbing small inequalities in the rails, and in passing bad joints, are materially less, and the wear on the wheels themselves is smaller. A gear ratio of 2 : 1 makes possible the use of a motor of, say, 500 r.p.m. with 40-in. drivers at a normal speed of 30 miles per hr. This is within the limits of economy.

The application of geared motors for low speeds may be made easily in the swiveling truck designs; or, if it is desired to concentrate the power in one or two large motors, a combination of gears and side rods may be made, as in Fig. 136. By this means the advantages of high center of gravity may be obtained. While the complication is somewhat greater, it appears to be justified, if one may judge by recent European designs.

Number and Coupling of Drivers.—An examination of existing designs of locomotives, both electric and steam, shows a wide range in the number of drivers, length of wheel base, and methods of coupling wheels together. The primary limitation of the track

is the maximum load which can be safely imposed by a single wheel. The best American practice, with first-class roadbed and track, limits the load per axle to from 50,000 lb. to 57,000 lb. These values are extreme, and should be used only when the track construction is the best. This limit will then determine at once the number of driving wheels necessary to give the desired tractive effort, if the adhesion coefficient is known. This latter is usually assumed, for purposes of design, at 22 per cent. to 25 per cent. A driving axle load of 50,000 lb. will then give a maximum tractive effort of 12,500 lb.; so that the weight on the drivers may be determined.

The weight to be carried on the idle axles depends largely on the maximum speed, character of the roadbed, and method of equalization. An inspection of the table on p. 243 shows the American practice for steam locomotives. For electric service the proportion of the weight on drivers may be somewhat greater, since there is no necessity for trailing wheels, which have been introduced in steam locomotive designs to allow an increase in the size of fire-box for large capacities.

The number of driving wheels which can be coupled together is limited by the total rigid wheel base permitted. This is determined by the radius of the maximum curves encountered, since the side play in the axle bearings is restricted. The length of rigid wheel base may be increased somewhat for slow-speed service by making some of the intermediate drivers without flanges; but, on account of danger of derailment at high speeds, this is not to be commended for passenger locomotives. In steam practice, the rigid wheel base will be from 10 ft. to 13 ft. for passenger locomotives, and from 10 ft. to 17 ft. for freight engines. Longer rigid wheel bases have been found destructive, both to the track and to the drivers. In steam service longer wheel bases have been made possible by the use of Mallet articulated locomotives, in which the driving wheels are assembled in two separate units, the forward engine being mounted on a swiveling truck. In electric locomotives, the result may be attained more simply by the use of separate units, operated together by multiple-unit control.

Evidence has been introduced to show that the tractive effort which can be developed by a locomotive will be increased if several driving axles are coupled together.[1] This is to be expected, since there is a certain amount of weight transfer between the

[1] Elmer A. Sperry, *Transactions* A. I. E. E., Vol. XXIX, p. 1453.

driving axles during acceleration and retardation. This point has already been considered in connection with train braking. For this reason it would seem advisable, if several axles are mounted on a rigid frame, to couple the wheels together, by means of side rods or by gearing. This action becomes apparent only while accelerating or retarding, so that for certain classes of service it may not be of great importance.

Interchangeability of Locomotives.—In many cases it is desirable to be able to use the same locomotive units for both freight and passenger service. When this can be done, the total investment in motive power is decreased, and the necessary repair work is simplified. The factors affecting the design, as it has been pointed out in this chapter, make it somewhat difficult to build a "universal" locomotive. If satisfactory for slow speed, it may not have the proper riding qualities for fast service; and if properly designed for high speed, it will be excessive in weight and cost when applied to slow-speed work.

When geared motors are used, it may be possible to approach the desired condition by using different gear ratios for high-speed and low-speed service, the mechanical design being otherwise the same. This reduces the number of separate parts, but does not make the equipment interchangeable. A compromise may be made in some cases by operating the motors at different potentials for the various classes of service. For instance, on a 600-volt direct-current locomotive, the motors may be placed in parallel for high-speed passenger operation, and in series-parallel for freight service. It must be remembered that the current capacity of the motors is not increased by this procedure, so that when running in series each motor is only giving about one-half its normal rating. On roads where most of the trains are in passenger or fast freight service, this method may give satisfactory results. The fact remains that, for the best operating efficiency, the locomotives should be designed particularly for the service they are to be used on; and if a compromise is necessary it must be effected at some loss.

Tractors.—A recent development in electric locomotive practice is to increase the capacity of the equipment by the use of auxiliary tractors. These, as used on one American railroad,[1] are four-wheeled motor trucks, which are operated in conjunc-

[1] Tractor Trucks and Additional Locomotives for Butte 2400-Volt Railway, *Electric Railway Journal*, Vol. XLIII, p. 1349, June 13, 1914.

tion with the locomotives. There is no control equipment on the trucks, but the motors are placed in series with those on the locomotive. The four main motors are wound for 1200 volts, and are operated two in series in normal service. When the tractors are used, the additional motors are connected one in series in each circuit, making three motors in series, and operating at approximately two-thirds normal speed in parallel, and one-third speed when all the motors are placed in series. Each tractor weighs approximately one-half as much as a standard locomotive, so that the drawbar pull is increased 50 per cent. by its addition. Using this method the flexibility of the equipment and its total capacity may be considerably extended at a fairly low cost. No operating data have been published to show the success of this arrangement.

Locomotive Equipment.—The equipment required for electric locomotives is, in general, the same as that in use on motor cars. The principal difference is in the capacity of the motors.

The location of the motors determines largely the position of the auxiliary apparatus on the locomotive. When geared or gearless motors are used, mounted directly on the axles, there is the entire space above the main frame available for control equipment. This does not ordinarily take up all the space, so that many locomotives of this class are designed with the so-called "steeple" cabs, as shown in Figs. 131, 132 and 134. When the motors are mounted on the frame, and coupled to the driving wheels with connecting rods, the space left for the apparatus is much less, and the cab is usually built over the entire locomotive frame. Such designs are shown in Figs. 133, 135 and 136.

The auxiliary equipment which is necessary on the ordinary locomotive consists of the controller, the resistors (if used), air compressor and governor, transformer (for alternating-current locomotives), and the miscellaneous apparatus needed for ease in operation. For use in connection with standard passenger cars, a boiler for supplying steam for heating is a necessity. All of this equipment is comparatively bulky; and in the latest designs the entire cab is filled with it, there being only a narrow passageway on each side.

Locomotive Control.—Due to the demand for independent units which may be operated together for increased output, practically all locomotives are provided with multiple-unit

control. On account of the large amounts of power handled, controllers of this type are almost essential in any case, since the capacities of hand-operated ones are not by any means adequate. It is interesting to note that in a recent European design, the controller is of the drum type; but this is an exception to the usual arrangement.

For heavy locomotive service, the variations in tractive effort which are allowable with motor cars would cause destructive jerking during acceleration. For this reason the number of steps on the controller is invariably greater. Since the acceleration may need to be varied to suit the requirements of each particular train, automatic control is seldom used, it being considered better practice to place the operation entirely in command of the motorman. With high-class employees, this method gives consistently good results.

Choice of Locomotives.—It may appear, at first sight, that the selection of the proper type of locomotive for a particular service is subject to exact rules. Such does not appear to be the case. The locomotives of competing manufacturers for almost identical service are so widely at variance that there can be no general agreement; and in some cases the same manufacturer has used entirely different designs for similar conditions.

Electric locomotives are still subject to great development; and it is quite possible that they may be standardized. It must be remembered that practically all of them in service have been designed within the past ten years, while the steam locomotives are the development of a century's study. It will not be remarkable if many years pass before the electric locomotive reaches the same condition of standardization as its steam competitor; and it is doubtful if this is desirable, for standardization on a large scale is liable to mean stagnation.

CHAPTER X

SELF-PROPELLED CARS

Field of Self-Propelled Cars.—Any railroad, whether steam or electric, has a comparatively high cost of construction. The gross receipts must be sufficient to cover the operating expenses, and leave enough margin to pay interest on the investment, before any profit can be realized. A certain class of roads exists in which operation by any of the ordinary methods, such as steam locomotives, or electric motors fed from a central power station, will not cover the expense. The steam locomotive, as has been shown, is at its best only in large units; and, if several trains per day are to be run, the cost of operating inefficient small locomotives may be prohibitive. On the other hand, the electric distributing circuit will be as expensive, in many cases, when but one car is run as when service is given every hour. The interest on the investment and maintenance charges will in this case prohibit successful operation.

It is for this class of roads that some form of low-cost, fairly efficient service must be given if a railway is to operate at all. Such is the case of many steam-road branches where, in order to develop traffic, the line has been built without sufficient knowledge of local conditions. Another instance is that where a railroad is desired to develop a new territory, but where the return may, for several years, be inadequate to pay expenses. Such a line is usually a feeder to a large steam or electric railway system. In other cases the cost of construction may be excessive. An example of this is the cross-town surface lines in New York City, where the overhead trolley is prohibited by law. To build underground conduit roads of the type used on the main through routes would cost much more than the traffic would justify. In each of these cases the demand is for a cheaply constructed track, and a motive power which will give satisfactory service at comparatively low cost. It is for this reason that the various self-propelled cars have been developed.

Self-propelled cars can also be used during hours of light load, such as at night. With infrequent operation of this sort it may prove economical to shut down the electric power plant entirely, giving the required service with self-propelled cars. In this way the no-load losses incident to a large system may be eliminated, while at the same time an opportunity is presented for inspection and repair to the power plant and substation apparatus.

At the present time, there are in use three different types of self-propelled cars, which cover the entire range of service needed. They are the gasoline type with mechanical drive, gasoline with electric drive, and the storage battery car.

Gasoline Cars.—All of the straight gasoline cars in the United States are of the same general class, being the product of one builder. The first of them were introduced about eleven years ago for use on unprofitable branch lines of the Union Pacific

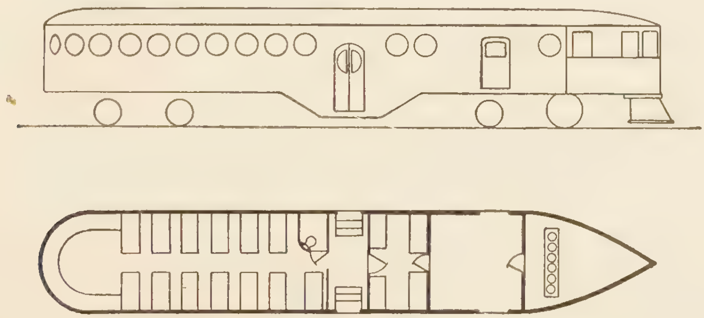

FIG. 138.—55-ft. gasoline car, mechanical transmission.

In this car the front axle is the driver, the engine being mounted directly above. Note the form of the car to reduce air resistance.

Railroad. The success met with in this service was so great that cars of similar type have been built for a number of roads in various parts of the country.

The gasoline driven cars are of somewhat special construction, as shown in Fig. 138. The forward end is reserved for the power plant, which consists of a 200-hp. internal combustion engine, directly geared to the front axle of the forward truck. Speed control is obtained in the same manner as in the gasoline automobile, by means of gears and a free engine clutch. Variations in the charge and the ignition allow still further range in the control.

The cars which are in operation are from 55 ft. to 70 ft. in length, and are somewhat similar to those for standard electric interurban railways. It is interesting to note that this design of car is the only one in regular service which has taken advantage of the experimental results found in connection with air resistance at high speeds. The front is wedge shaped, while the rear end is rounded. The roof is of the plain arch type, and all of the fittings, such as windows and doors, are so designed as to give the most regular contour possible. The builders claim a materially reduced train resistance due to the construction.

Gas-Electric Cars.—There are two distinct types of gasoline-electric cars in use in America, both of which embody the same general features. One of the cars of the General Electric Company is shown in Fig. 139, and a similar one, manufactured by the

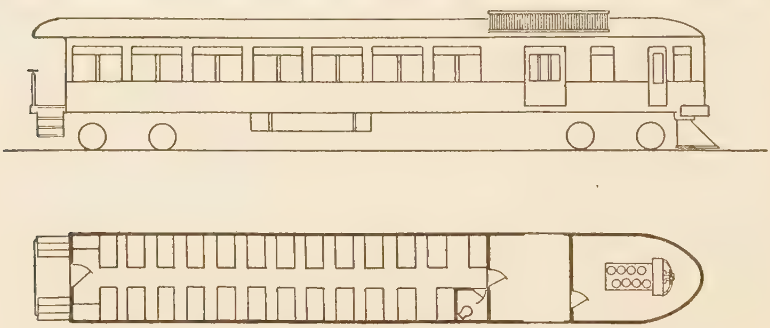

Fig. 139.—70-ft. General Electric gas–electric car.
The gasoline engine drives a direct-current generator from which current is obtained for operating the railway motors.

Drake Railway Automotrice Company, is shown in Fig. 140. In either the power plant consists of an internal combustion engine, driving a direct-current generator, current from which is used to operate standard 600-volt motors. A special form of series-parallel controller is used, which, instead of inserting resistance in series with the motors, varies the field strength of the generator. By this method the control is made more efficient than with the direct mechanical drive; and, since the motors are able to deliver maximum tractive effort at low speeds with correspondingly reduced power input, the total capacity of the power plant can be less than for the direct drive. This allows a lighter gasoline engine; but the weight of the entire equipment must necessarily be somewhat heavier for the electric transmission, since a generator and a set of motors must be added.

In practice, the operating costs for the three types of gasoline cars are approximately the same, varying with the severity of the service and the weight of the equipment. Either type is fully capable of hauling one or more trailers when required, so that the apparatus is exceedingly flexible.

Storage Battery Cars.—The storage battery car is one of the oldest developments in the history of electric traction, being antedated only by those driven by primary batteries. In the early experiments, batteries of the types obtainable at that time were tried and abandoned, largely on account of the great weight of the equipment. The recent improvements in storage battery design and manufacture, due largely to the advent of the electric automobile, have made it possible to obtain batteries having

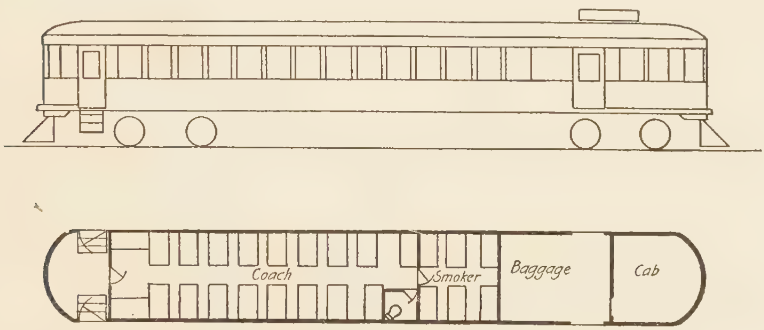

FIG. 140.—70-ft. Drake "automotrice."
This car is similar to that shown in Fig. 139, but is of somewhat lighter construction.

much greater output per pound of weight, with increased life. This development has made their use practical for propelling railway cars with a reasonable efficiency.

There are several different kinds of storage battery car in use at the present time, differing principally in the type of cells employed. Both the lead and the Edison nickel-iron batteries are used, and appear to be giving satisfaction. One type of car, following largely the double-truck stepless design of the New York Railways, and in use on the same road, is shown in Fig. 141.

In any of the storage battery cars, successful operation depends on having the body as light as possible, since the size of battery to be used is a direct function of the weight hauled. Much attention has been paid to this feature, and exceedingly low weights per seat have been attained. In addition, the bearings are of the anti-friction types, such as roller or ball bearings. Since the

17

car speeds in the service for which storage battery cars are best fitted are low, the train resistance consists largely of journal friction; and by the use of such bearings it may be diminished considerably. Some of the makers go a step further and use a rigid axle with two independent wheels, as in ordinary wagons. It is claimed that this reduces the friction still more, especially on curves. No extended experiments have been made to prove this, and it is possible that the lower friction on curves may be offset by increased oscillatory resistance.

There are two different methods of operating the batteries. One maker advises that they be of sufficient capacity to give a

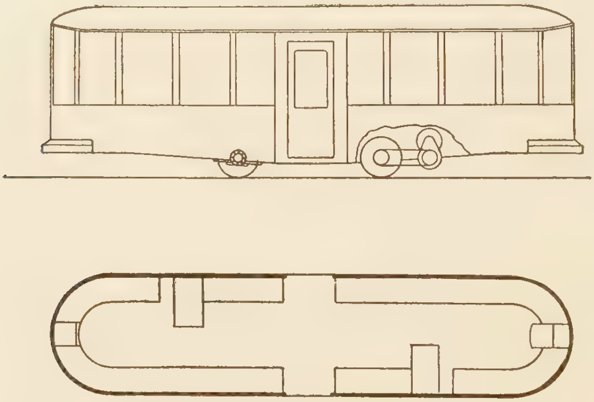

FIG. 141.—Stepless storage battery car.

The batteries are placed under the seats. The motors are connected independently to the wheels by chain drive. Friction is reduced by using ball- or roller-bearings.

whole day's run without recharging, while others recommend a smaller battery, with a full charge once a day, and short "boosting charges" at the end of each trip. While this latter method allows the use of a battery of less capacity, it does not give such flexibility in service. For instance, if a car is late in arriving at the charging station, it will not receive sufficient charge, and the battery may be exhausted before the day is over, or else the schedule will be disarranged. Trouble has resulted in a number of cases from this cause, and has made it an open question as to which is the better method of operation.

The motors for storage battery cars are much smaller than those for standard electric railway service with equipment of equal weight. This is largely due to the fact that the acceleration

and the maximum speeds are low. With high acceleration the size of battery required becomes so great as to render its use impractical.

Storage battery cars are controlled by series-parallel connections of the batteries, instead of the motors, although by combining the two methods three economical running speeds may be obtained. Otherwise the arrangement is the same as for standard railway equipment. The cars may easily be arranged for multiple-unit control; and in some cases are so operated.

Comparison of Self-Propelled Cars.—It is evident that the various types of self-propelled cars have different fields of service. Any of the gasoline-driven cars are capable of operation over any length of line, and are limited only by the requirements of obtaining fuel and having sufficient time at terminals for inspection and repair. Storage battery cars, on the other hand, are restricted in action by the amount of charge, and must run only between points where electric current is available. There must be a certain time of inaction during charging, whether it is for a single long period per day, or at the end of each trip.

The gasoline drive may be suited to the weight hauled, so that there is no limitation to the size of car which can be equipped with this type of motive power, while the storage battery increases in bulk quite rapidly with the weight. This condition is inherent, and cannot be overlooked in any comparison.

It appears that the gasoline drive is best suited to units of comparatively large weight, which must run over considerable distances, and at fairly high speeds. The choice between the mechanical and the electric drives depends on the need for smooth acceleration, and efficient operation over a wide range of speeds. The running expenses are nearly the same for both types; but the first cost of the gas-electric cars is somewhat higher, owing to the greater amount of equipment. They are also slightly heavier for the same capacity. The wide use of gas-electric cars at the present time would indicate that the smoother operation is of sufficient value to warrant the extra cost and weight. Storage battery cars are better for local service where traffic is sparse, or where conditions are such as to prohibit the use of overhead trolleys.

It is not to be expected that the use of independent units will ever supersede the ordinary electric railway with a central power plant for general service, for a limit to the field of the self-

propelled car is reached with a comparatively low traffic density. This can be determined by calculating the fixed charges and running expenses of the two methods. On comparison it will be seen that the operating cost of any form of self-propelled car is higher than that for standard electric equipment; and the first cost is also greater. As the number of cars in use increases, the fixed charges on the power plant and distribution system become proportionally less; and when the total cost becomes equal in the two cases, the advantage of the independent units disappears. Actual comparisons show the field of this class of vehicle to be limited to that stated at the beginning of the chapter. For these special forms of service the self-propelled car furnishes a valuable auxiliary to a large railway system, and may increase the earnings or decrease the expense by a considerable amount.

Gasoline and Special Locomotives.—The arguments in favor of self-propelled cars do not apply with equal force to locomotives, since the steam locomotive is quite satisfactory for nearly all classes of service. The success of the internal combustion motor has led engineers to believe that there is a field for engines of this class, and several designs have been made. At present a few locomotives with internal combustion motors are in service. A road having a small amount of freight business, and operated either by the electric system or by self-propelled cars, may have need of such a unit.

The mechanical and the electric drive have both been applied to internal combustion locomotives. One type of the latter, in conjunction with the Diesel crude oil engine, has been used in Europe for some time.

In connection with the electrification of the railroads entering Chicago, a proposition was made several years ago to use storage battery locomotives. While there is no question but that such equipment is a possibility, it is extremely doubtful whether it could show sufficient economy in operation to justify itself. Undoubtedly the total running cost would be much greater than for any standard form of electric system working on a distributing circuit from a central power plant.

CHAPTER XI

ELECTRIC RAILWAY TRACK

Track Construction.—Although the requirements of all railway track are essentially the same, there are two distinct types of construction used, depending on whether the railroad is laid on private right-of-way or in paved streets. A large portion of all interurban roads are built on private property; and in all such cases the ordinary construction adopted by steam roads can be used to advantage. The rails are of standard T-section, the size being chosen with regard to the amount of traffic and weight of trains.

In track construction the primary consideration is good drainage. There should be a well-settled foundation of the natural soil, above which is placed a layer of broken stone or

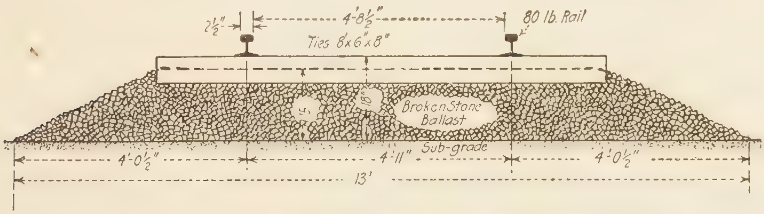

Fig. 142.—Standard interurban track construction.

gravel ballast, from 8 to 12 in. in thickness. On this are placed the cross-ties, and the space between them filled with the ballast, which should be well tamped beneath the ties to secure them firmly in place. With this construction, the porous stone ballast will allow surface water to drain off readily, and so keep the foundation dry. It is necessary to provide ditches along the side of the roadbed, at a level below the bottom of the ballast, in order to drain off the water which has collected on the track. In this way the entire structure will be more permanent and will require less maintenance than where the roadbed has been poorly built. A typical form of railway roadbed is shown in Fig. 142.

The ties in use are generally of hard wood, such as cedar, oak or chestnut. At the present time it is somewhat difficult

to secure a good grade of such materials; and the practice of using soft wood ties, such as pine and hemlock, but impregnated with some preservative compound, has spread rapidly. The chemicals in general use are creosote and zinc chloride. These are applied in liquid form, the ties being treated either in the open air or in vacuum tanks. While the latter process is more expensive, it gives a more uniform application of the preservative, and causes it to sink much deeper into the fiber of the wood. Treated ties are considerably more expensive than untreated ones; but the soft wood, when properly impregnated, has at least as good life as the natural hard wood, and the cost is no greater. When hard wood is treated in the same manner, its life may also be proportionally prolonged at a comparatively low cost. Indeed, it has been possible to prevent decay to such an extent that the life of the tie is determined by mechanical wear from the chafing of the rails, and the destruction of the fibers by driving spikes.

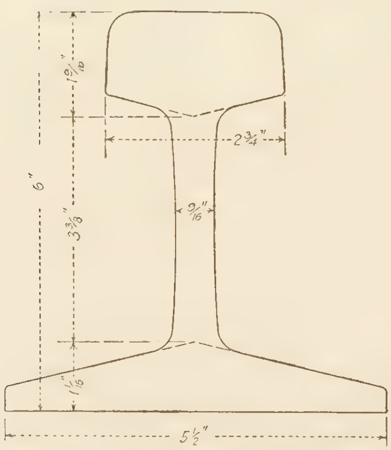

FIG. 143.—Standard 100-lb. T-rail.
This is the standard T-rail adopted by the American Electric Railway Association. Other sizes are quite similar in shape.

In the older track construction the rails are laid directly on the ties, and are fastened in place by common spikes. The mechanical wear on the ties in such construction is severe, and even untreated ones may be rendered unfit for further service before they have decayed. With the use of preservatives, and the consequent increase in life, many roads have adopted the practice of placing tie plates under the rails to take the wear. Another advance is in the use of screw spikes instead of the common driving spikes. This further increases the life of the ties.

Track Rails.—The rails in use are of the standard sections adopted by the American Society of Civil Engineers, the American Railway Association, or the American Electric Railway Engineering Association. A section of the standard 100-lb. rail adopted by the latter is shown in Fig. 143. The weights used vary

from about 60 lb. per yd. to 100 lb., the majority of rails being from 70 to 80 lb. for interurban construction.

The chemical composition of rails has a marked effect on their physical properties, and on the results which may be obtained from them in service. Where the roadbed construction possesses sufficient flexibility, the composition may be such that the metal is tough, but fairly soft. For use in paved streets, where the sub-base of the track is rigid, as when laid with concrete, a harder rail, possessing greater resistance to wear, is desirable. The hardness depends to a large degree on the content of carbon, although a number of different elements, such as manganese, titanium, nickel, chromium, silicon, etc., may be added to vary the properties of the steel. In general, since the wheel loads on electric railroads are much less than for steam trunk lines, the composition may be selected to give greater hardness, even though the metal may be more brittle. The recommendations of the American Electric Railway Engineering Association for rail metal are as follows:[1]

Elements	Per cent.	
	Class A	Class B
Carbon	0.60 to 0.75	0.70 to 0.85
Manganese	0.60 to 0.90	0.60 to 0.90
Silicon	Not over 0.20	Not over 0.20
Phosphorus	Not over 0.04	Not over 0.04

Rail Joints.—The connection between rails is of vital importance. Rail joints are either suspended or supported, depending on whether the joint is placed between two adjacent ties or on top of one tie. The forms in common use are numerous, and both methods of support are used. The connection between rails is made by means of two plates, known severally as "joint plates," "splice bars," "angles" or "fish plates." These are of special rolled sections and are placed one on either side of the rail ends, being bolted to each rail. The simpler forms, such as shown at (*a*) in Fig. 144, consist of a pair of plates which are drawn in against the base and head of the rail by bolts. This form of joint may be either suspended or sup-

[1] *Engineering Manual*, American Electric Railway Engineering Association, Section *Wr 2c*.

ported. The "continuous" rail joint is shown in Fig. 144 (*b*). In this the plate is continued down beneath the base of the rail, forming a chair. A number of joints of this general design are in use both on steam and on electric roads.

Track Construction on Paved Streets.—In cities, where the streets are paved, it is necessary to build the track in such a manner as to interfere as little as possible with the surface of the paving. The standard T-rail construction may be used, the paving being laid on top of the ties so as to bring it flush with the head of the rails. Since it is necessary to allow space for the wheel flanges on the inside of the track, special paving blocks

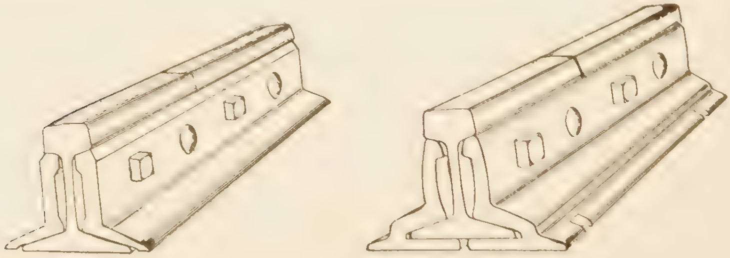

Fig. 144.—Types of rail joints.
(*a*) Common fish-plate joint. (*b*) Continuous rail joint.

are sometimes used to give the necessary groove. While this is satisfactory where the travel is not very heavy, it is not so good on streets which are much used for heavy teaming. The height of the ordinary T-rails is not sufficient to use standard paving blocks with a cushion of sand deep enough to give good wear. This defect may be remedied to some extent by using special rails with a high web, and having the head and base the same as the standard T-section. In many of the large cities provision is made that the street railway tracks must be available for wagon traffic; in some it is provided by law that a rail of a tram section, such as that shown in Fig. 145, must be used. In others, where such regulations are not in effect, the railroads have sometimes laid rails with a grooved head, as in Fig. 146. This provides no path for vehicles, which is a good thing from the standpoint of the railway. When the tram section of rail is used, it makes an excellent roadway for vehicles, the wheel treads running on the projecting lips of the rails. The difficulty in its use is that if the lip is below the rail head a

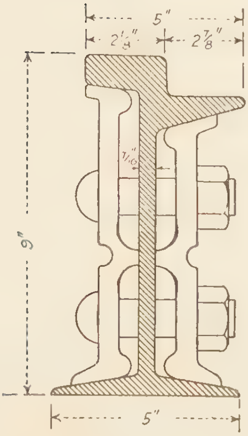

FIG. 145.—Tram section girder rail.

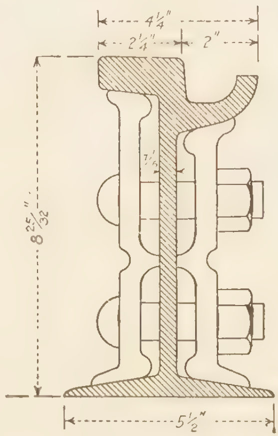

FIG. 146.—Grooved section girder rail.

Both of these sections have been used to a considerable extent for street railway track, but are now almost entirely superseded by rails of the general type shown in Fig. 147.

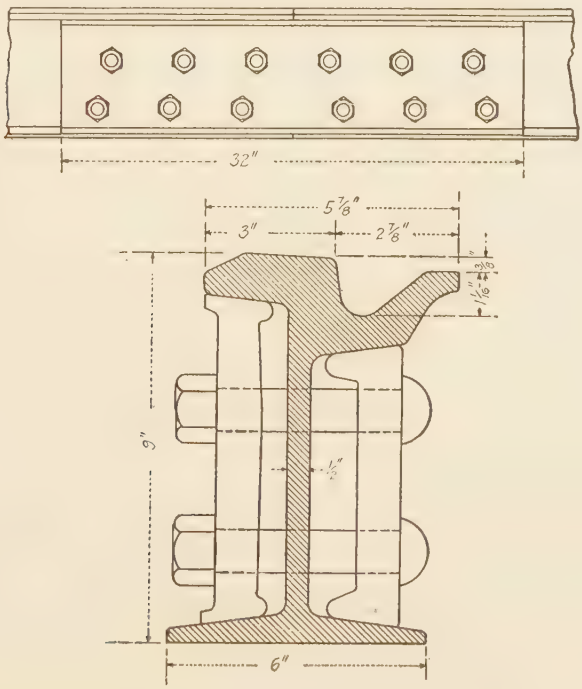

FIG. 147.—9-in. Girder rail and joint plates.

Used in city construction on paved streets.

sufficient distance to allow the use of a standard wheel flange, it is hard to get vehicles out of the path of cars, thus delaying traffic. A compromise has been effected by the use of the grooved rail in such a form that the lip is far enough below the head to provide a runway for vehicles, and at the same time make it easy for them to leave the tracks. The design for a 9-in. girder rail with joint plates, as standardized by the American Electric Railway Engineering Association, is shown in Fig. 147. This or similar designs have been adopted in many of the large cities of the country, and have proved satisfactory.

Special Forms of Rail Joints.—While the various forms of mechanical joints made by splice bars and joint plates are entirely satisfactory in open construction, they must be carefully maintained and tightened as the bolts wear loose. This requires constant inspection. It is evident that where the track is laid in city streets, and completely surrounded with paving, such care is impossible. It is essential that the joints remain in good condition with no inspection whatever, and that the repairs be very few, since each time one is made it means to tear up and replace the paving around the joint.

A method which has been used in many cities is to weld the rail ends together, thus forming a continuous structure. This arrangement cannot be used in open track, since the expansion and contraction will tear the track loose from the ballast with every change in temperature; but in city streets it can be employed to advantage, since the rails can be anchored firmly by the paving, so that the temperature changes can only place the rails in tension or compression. As the rails are usually laid in the hottest days of summer, the track will be in tension for nearly the entire year, and there will be practically no tendency to buckle. It is evident that this construction cannot be used to advantage on curves.

Cast Welded Joints.—There are three methods of track welding which are in general use. The oldest is the cast weld. In this construction, shown in Fig. 148, the rail ends are joined by a mass of cast iron surrounding them. The iron is melted at a high temperature and poured into iron moulds around the rail ends. This chills the outside surface of the cast metal, so that the interior has its temperature raised to a welding heat, and an actual weld is made with the steel of the rails. This form of joint is quite satisfactory, the principal objection being that extreme cold

weather may strain the cast metal beyond its tensile limit and crack the weld. From one to two per cent. fail in this manner.

Thermit Weld.—Another method of rail welding is by the use of "Thermit." This is a patented mixture consisting of metallic aluminum and iron oxide in proper proportions, with other materials added to obtain a metal of the required composition. This is supplied in the form of a powder, which, when ignited, undergoes a chemical reaction, the aluminum combining with the oxygen to produce alumina and metallic iron at a high temperature. The powder is placed in crucibles directly above the rail joints, which have been previously heated by some external means. The mixture is ignited, and when the reaction is complete the molten iron is tapped into moulds around the rail ends. The weld

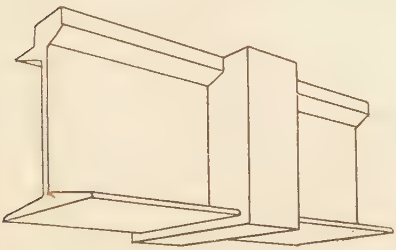

FIG. 148.—Cast weld.

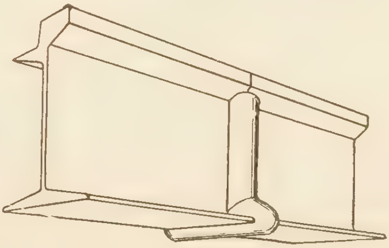

FIG. 149.—Thermit weld.

produced is not unlike the cast weld; but the metal is of a different character, being of the composition of wrought iron or steel, depending on the ingredients of the mixture employed. The temperature of the molten metal is much higher, so that a more perfect weld is obtained, and the amount of iron required is considerably less than for the ordinary cast weld. The appearance of a thermit weld is shown in Fig. 149.

Electric Welding.—The third way of welding is with the aid of the electric current. There are two distinct methods which may be used. In the first, which has the widest application, joint plates are welded to the sides of the rail ends by the incandescent or resistance process. This consists in taking current from the contact line, converting it to alternating current by a rotary converter or motor-generator set, and changing to a low potential through a stationary transformer, whose secondary winding consists of a single turn of heavy bar and terminates in jaws which are placed against the parts to be welded. The diagram of con-

nections is shown in Fig. 150. The resistance in the secondary circuit is practically all concentrated at the junction between the rail and the joint plate; so that a considerable amount of heat is generated there, and the temperature is raised to the welding point. By applying a suitable pressure to the jaws, an actual union of the metals is obtained. The entire rail section is not welded; but two or three places on the end of each rail suffice to make a more permanent connection than is possible with any of the usual forms of mechanical joints.

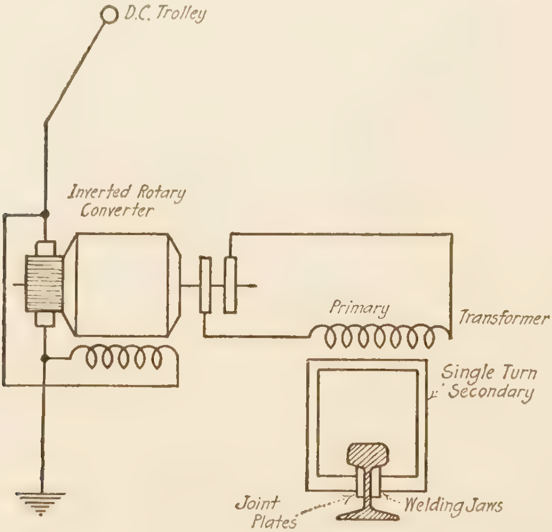

FIG. 150.—Diagram of connections for electric welding outfit.
For welding rail joints. A similar set, except of smaller capacity, is used for welding bonds.

Within the last few years another system of welding has been developed, using the arc method. In this the rail is made one terminal of the electric circuit, and a rod of carbon the other. The heat generated when an arc is struck between the carbon electrode and the rail is sufficient to raise the metal to a welding temperature, and even to melt it. By this means plates may be welded to the rails, thus forming permanent joints.

Of the four methods of welding, the "Thermit" process requires the least expensive apparatus, and for that reason is applicable to roads which could not afford the more costly equipment. The arc, the cast, and the resistance welds require more expensive apparatus in the order named. The actual cost of

each joint depends largely on the number to be made. The equipment for electric resistance welding is so expensive that it is ordinarily not purchased outright by the railway company, but is rented from firms making a specialty of the business. The cost of making joints varies from about $2.75 for cast welds to $4.50 for "Thermit" and $6.00 for electric welds by the resistance process.

Special Work.—In any railroad, it is not sufficient to provide a single track alone, but switches, turnouts and crossings must be used, their number and complexity varying with the nature of the track. Such pieces are almost invariably built by manufacturers who make a specialty of this business, and are installed by the railroads as complete units. For interurban roads, the number of different parts is relatively few, and they may be kept in stock by the user. But for railways whose tracks are built in city streets, it is essential that the construction be such that the parts can be installed with a minimum of difficulty, and that they will give a maximum life, since the replacement is a difficult piece of work, requiring that the traffic be stopped and the paving removed. To make the installation as simple as possible, the entire track layout for a switch or crossing is built complete by the manufacturer, and assembled in his yards prior to shipment. When it is desired to replace one piece of special work by another, the parts are set up in the street near the final location, while the paving is removed from around the old track. At a period of light traffic, usually at night, the old track is removed and the new slid into position, it having been fitted previously by measurement so that a minimum of adjustment is necessary.

The frogs, switch points and mates are the parts which receive the greatest wear. In recent years it has been found possible to increase the life of the special work by making these wearing parts of special materials, manganese steel being used very largely for the purpose. The hard inserts may be cast permanently in position, or may be made in such form that they are bolted and wedged in, so that they may be removed and replaced. There is always some danger of these parts becoming loose under the repeated hammering of the wheels; and at the present time this is one of the difficult problems of track maintenance. It is beyond the scope of this book to take up the details of special work design; but much information on the subject may be found in the current engineering periodicals.

CHAPTER XII

THE DISTRIBUTING CIRCUIT

The Electric Railway Circuit.—The problem of distributing electrical energy for railway service by means of a constant potential system is theoretically the same as for lighting and power, but it differs therefrom due to the changing location of the load. It is this characteristic which differentiates railway distribution most radically from other constant potential circuits.

No matter whether the generating system is connected directly to the distributing circuit, or through a transmission system and substations, the electrical relations in the contact line and the

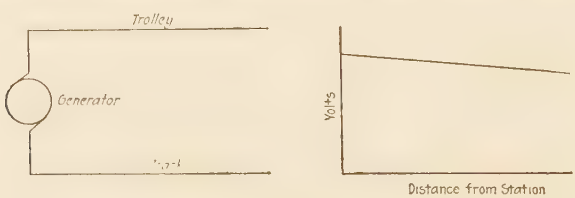

Fig. 151.—Simple distribution circuit.

The generator is at one end of the line, feeding directly into the trolley wire. The diagram at the right shows the potential at any point when the car is at the far end of the track.

auxiliary conductors are essentially the same. In the following discussion it is understood that the terms "substation" and "power station" may be considered synonymous so far as the distributing circuit is concerned, the difference between them relating to other parts of the complete power system which will be discussed elsewhere.

The general considerations of the constant potential circuit necessitate at least two conductors between which the load may be connected. Since the point of application of the load is constantly changing, it is essential that these conductors be bare to allow the moving contacts free access to the surface. In a very large proportion of all electric railways the track rails are utilized for one side of the circuit, contact being made through the wheels, while a wire or rail is used for the other conductor. This arrange-

ment causes such wide differences in the two sides of the circuit that it is generally simpler to consider them separately.

The simplest railway distribution consists of that for a single-track road fed from one end, as shown in Fig. 151. If we consider this line operating a single car, it will be seen that at the substation the full potential of the generating machine is directly available, since the drop in the wiring is practically negligible. As the car goes farther from the station, the drop in potential increases, being greatest at the distant end of the line. If a constant poten-

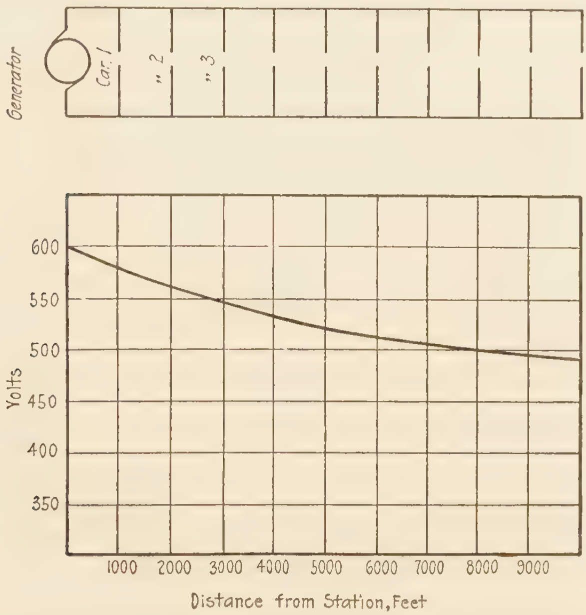

FIG. 152.—Line drop for simple distributing circuit supplying several cars. The circuit is the same as that shown in Fig. 151, but a number of cars are being operated, instead of one as in the former case.

tial is delivered, the drop will increase directly with the distance from the station, its value being determined by the current and the resistance of the conductor. A potential diagram is shown in the figure. If the station potential is 600 volts and the car is at the end of the line, drawing such current as to give a line drop of 110 volts, the average pressure supplied to the car is evidently 490 volts if the current demand is uniform. Although the current will vary within wide limits, its average value will follow this law. The limiting condition will then be to determine the greatest

permissible drop with the maximum current; from which, by Ohm's law, the size of the conductor required may be found.

The single-car line is seldom met with in practice. Usually, a number of cars will be operated on the road; and if they are all demanding current in equal amounts, the distribution of the potential drop will be quite different from that in the example just given. Consider ten cars equally spaced along a line 10,000 ft. long. If each is demanding a current of 100 amp., the total to be delivered, or 1000 amp., will be carried from the station to the first car, 900 amp. from that point to the second car, and so on, until at that portion of the line beyond the ninth car the current is but 100 amp. If the total resistance of the line is 0.2 ohm, the drop in potential will be as shown in Fig. 152, being greatest near the station and least at the end of the line.

Had the entire load been placed at the end of the line, the total drop would have been

$$0.2 \times 1000 = 200 \text{ volts}$$

and the pressure at the end of the circuit

$$600 - 200 = 400 \text{ volts}$$

as shown by the dotted line on the diagram. It may also be seen that with the entire load concentrated at a point 5500 ft. from the station, the drop would be the same as in the actual distribution. An inspection of the figure shows that this is the average distance of the load from the station.

In the general case, if the total load is made up of a number of currents I_1, I_2, I_3, etc., located at distances d_1, d_2, d_3, etc., from the station, along a conductor whose resistance *per unit of length* is r, the total drop e at the farthest point is

$$\begin{aligned} e = {} & rd_1(I_1 + I_2 + I_3 + \ldots\ldots + I_n) \\ & + r(d_2 - d_1)(I_2 + I_3 + \ldots\ldots + I_n) \\ & + \ldots\ldots + r(d_n - d_{n-1})I_n \end{aligned} \tag{1}$$

Equation (1) may also be written in the form

$$e = r(d_1I_1 + d_2I_2 + d_3I_3 + \ldots\ldots + d_nI_n) \tag{2}$$

It is often desirable to get the "center of gravity" of the load, which is usually defined as the point, d, at which, if the load were concentrated, the drop would be the same as with the actual distribution, or

$$e = rd\,\Sigma(I_1 + I_2 + I_3 + \ldots\ldots + I_n) \tag{3}$$

The last term of this expression is evidently the total current, I, delivered to the system. Using this value, and equating (2) and (3), gives

$$d = \frac{d_1 I_1 + d_2 I_2 + d_3 I_3 + \ldots \ldots + d_n I_n}{I} \tag{4}$$

In the special case where the loads are all of equal amount, and are uniformly spaced, this becomes

$$d = \frac{d_1 I_1 + 2d_1 I_1 + 3d_1 I_1 + \ldots \ldots + nd_1 I_1}{nI_1}$$

$$= \frac{d_1 I_1 (1 + 2 + 3 + \ldots \ldots + n)}{nI_1}$$

$$d = d_1 \frac{n + 1}{2} \tag{5}$$

As the number of divisions n is increased indefinitely, $\frac{n+1}{2}$ becomes equal to one-half the total number of divisions, and the second member of equation (5) approaches a value of d of one-half the total length of the distribution. This is a special case; but on roads operating a considerable number of cars on a uniform headway it is very nearly reached. This is shown by reference to Fig. 152. If the load were uniformly distributed in this case, the average distance would be 5000 ft.; with the given arrangement it is 5500 ft. If the cars each moved 1000 ft. toward the station, there would be no drop for the first one, and the average distance (center of gravity) would be 5000 ft.

Use of Graphical Time-Table.—The application of this principle depends on knowledge of the actual distribution of the load; in preliminary work it cannot be known, and must be assumed. After the equipment has been tentatively decided on, the speed–time curves for the various runs may be calculated, and from them the schedule made up. In practice the time-table is laid out graphically, as in Fig. 153, using time as abscissæ and distance as ordinates. It may be seen at once that this consists of a set of distance–time curves, which may be readily determined from the speed–time curves by integration. Corresponding to the various abscissæ, the currents being taken by the cars may be found, and the total gives the load to be distributed over the section in question.

Limiting Drop.—The determination of the proper value for the limiting drop is the most difficult part of the problem.

Direct-current series motors will operate with some degree of satisfaction, even though the line pressure be far below the rated motor potential, but will run at lower speed. It is simply a question of how much speed reduction will be tolerated under the worst conditions of load and distribution. With alternating-current induction motors, the speed is not changed greatly with reduced potentials, but the maximum torque and the performance of the machines will be much more seriously affected. Single-phase commutator motors have about the same relations

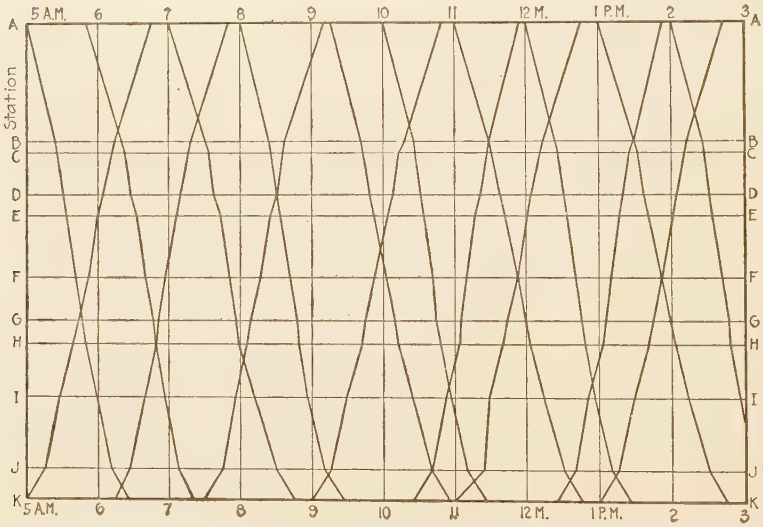

Fig. 153.—Graphical time-table.

Showing the location of all cars on a division at any instant of time. This is taken from the time-table of a 30-mile interurban railway division.

to change in potential as direct-current motors; and, since they may be connected to different taps on the transformer, the net effect will be still less. In general, the permissible drop is usually given as about 10 per cent. for city systems, 15 per cent. for suburban systems using direct current, 25 per cent. for direct-current interurban roads, and 10 per cent. for alternating-current lines. These values are very often exceeded.

If the motors were the only apparatus using the trolley current, the drop would be of little moment except as it changes the motor characteristics. But there is a certain amount of auxiliary equipment, such as air pumps, lights and heaters, which must also receive its energy from the line, and whose performance is

more seriously affected. Air compressors become overloaded when operated on reduced pressure, lamps have their candle power lowered as about the fourth power of the potential, and heaters their heating capacity as the square of the potential. For these reasons it is desirable to have fairly good regulation.

In certain cases the section of conductor calculated to give the maximum allowable drop will be found wasteful from the standpoint of energy loss. The most economical section may be determined with the aid of Kelvin's law, which is, in effect, that the minimum annual cost of the line is reached when the cost of the annual power loss is equal to the value of the interest and depreciation on the investment. The application of this law to any complicated distribution system, such as that for a city railway, is exceedingly difficult; but for a simple single-track interurban line it admits of solution. Unfortunately, in the latter case, the most efficient section of conductor is almost invariably smaller than that warranted by the maximum permissible drop.

Methods of Feeding.—A further reference to Fig. 152 shows that when the load is evenly distributed along the line, the drop is not by any means uniform, being much greater near the station. It would seem preferable to enlarge the conductor section near the station, even if the resistance at the far end of the line had to be increased, since there the maximum possible current is quite small. If the same amount of conductor material is properly arranged with reference to the current it must carry, it will be of a maximum section at the station, gradually tapering down to a small size at the extreme end of the line. Practical considerations make the complete fulfilment of this arrangement out of the question; there must be a contact line of fairly large section to withstand the wear incident to current collection. If this is the only conductor which need be installed to give the required section, there is no remedy for this condition; but usually a supplementary conductor must be added to limit the drop to the amount determined as the maximum allowable.

The simplest method of distribution from a power plant or substation is that shown in Fig. 151, where the generator is connected directly to the contact line, there being no auxiliary conductor. A consideration of the preceding paragraphs will show that this is uneconomical of copper, since the section should be increased where the drop is the greatest. It has been intimated that the best conductor is one gradually tapering from a

maximum at the station to a minimum at the end of the section; but such an arrangement is not commercial and cannot be applied directly.

The most usual method of feeding, especially for interurban roads, is to place a supplementary conductor in parallel with the contact line, connection being made at frequent points, as shown in Fig. 154. This arrangement is but little better than increasing the section of the contact line, although the supplementary wire

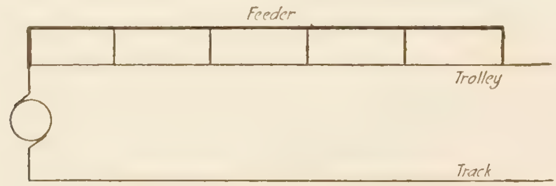

FIG. 154.—Simple feeder system.

This is little more than the equivalent of increasing the section of the contact line. It is widely used on interurban railways.

can be protected from wear and therefore have a minimum rate of depreciation. In interurban systems, taps are made from the feeder at from every 500 ft. to every 2000 ft., depending on the character of the road. Taps are made more frequently on grades and at points where the cars must be accelerated.

Another method of feeding is to separate the contact line into a number of sections, each supplied from the same feeder, as

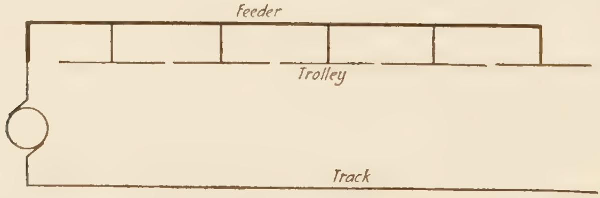

FIG. 155.—Sectioned conductor.

This arrangement differs from that shown in Fig. 154, in that the trolley wire is cut into sections which are separated by insulators. While giving protection in case a section of the circuit is damaged, the loss is considerably greater.

shown in Fig. 155. This arrangement has the advantage over the system shown in Fig. 154 that contact line trouble can be localized by placing fuses or circuit breakers in the feeder taps. On the other hand, the conductivity of the contact line is not used to its fullest extent, so that a larger amount of copper is needed to give the same total drop.

A modification of the first method is shown in Fig. 156. This differs from the simple system in that the feeders are run separately, their conductivity being chosen to equalize the drop to some extent. By careful choice of the size of conductors, the drop may be made fairly uniform over the entire section.

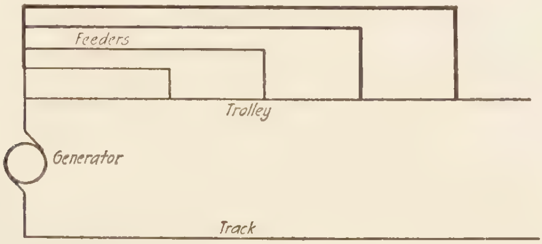

FIG. 156.—Multiple feeder system.

In this system the feeders are placed in parallel. Their size is so proportioned as to equalize the drop at the points of connection with the trolley wire.

A method sometimes used is shown in Fig. 157. Here the feeders are arranged as in the last system, but the contact line is sectioned as in Fig. 155. The objection is the amount of copper required for a given drop; while the advantage is in a more uniform drop over the entire section and the ability to localize troubles. It is evident that in this arrangement switches to the

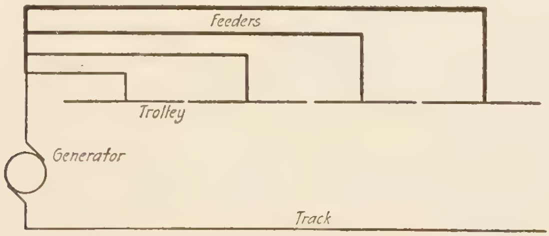

FIG. 157.—Sectional feeder system.

This is similar to Fig. 156; but the trolley is divided into sections separated by insulators. They may be connected together for normal operation by switches, making it possible to cut out of circuit a damaged portion of the contact line, and thus maintain partial service.

various feeders can be provided on the switchboard, and, with automatic circuit-breakers, any damaged section can be cut out of the circuit without affecting traffic on other portions of the line.

Use of Boosters.—On certain long lines, the ordinary limitations of maximum drop would require the use of very large feeders. This may be obviated to any desired degree by inserting

in one or more of them a separate series generator, known as a "booster." Such an arrangement is shown in Fig. 158. Here a simple feeder system is used for a portion of the section, but in order to keep up the pressure at the far end, a booster is inserted in the longest line.

As used on electric railway distribution circuits, the booster is a series-wound generator, driven by an engine or a motor, and having its field and armature connected directly in the feeder circuit, as shown in Fig. 158. The number of turns on the field winding is chosen to give the proper e.m.f. at full load to compensate for the drop in the feeder, or if desired, to over-compound and raise the pressure with the load. Such an arrangement is automatic in action, for the ampere turns on the field increase directly with the current, and, if the field is not

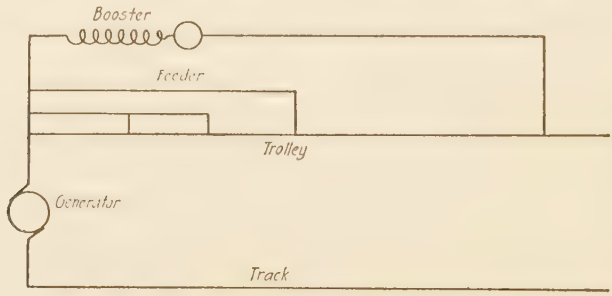

Fig. 158.—Use of booster for feeding system.

saturated, the e.m.f. generated in the armature is in proportion to the load. The compensation for line drop at the end of the feeder may therefore be taken care of under all conditions of operation, without the necessity of constant attention by the station attendant. Boosters may be located anywhere on the feeders in which they are inserted; but are commonly placed in the substation, since there they are under the supervision of the operator. The use of a booster does not reduce the drop. The tendency is rather to augment it; but by increasing the e.m.f. on the feeder the pressure at the end of the line is kept at the desired value. At the present time, boosters are being abandoned in favor of better location of substations.

Requirements of the Contact Line.—We have seen that the distributing circuit for an electric railway differs from that for any other application of electricity principally in that the load

is never fixed in location. The effect of this, apart from all questions of capacity, is that a special form of construction must be employed to permit of efficiently connecting the load with the source of power. This movable contact must have as little resistance as is practicable, and it must be reliable under all conditions of load and weather. To attain these desired criteria has been the aim of designers of electric railway apparatus from the beginning, and at the present time a great deal has been accomplished toward these ends. Contact line material may be made as reliable as conditions warrant, and failures of first-class construction are now rare.

Forms of Contact Line.—There are in general use at the present time two methods of distributing electrical energy to the moving train: the overhead trolley and the third rail. In addition to these, two other forms, the underground conduit and the surface contact system, have been used to a small extent. The first two are the only ones which have any extended application, and are to be looked to for future developments.

The Overhead Trolley.—The simplest method of distributing energy to a moving train is by means of one or more bare wires strung above and parallel to the track. If a direct-current or single-phase circuit is used, the track may be made the return conductor. By this means the contact line is reduced to its simplest terms: a single wire, arranged to make connection with the moving train through one or more rolling or sliding contacts. In this form the overhead trolley has become standard on a very large proportion of all the electric roads of the world.

Methods of Suspending Trolley Wire.—Practically all overhead trolley wires are arranged to have the moving contact made on the *bottom* side of the conductor. To make this scheme successful, it is necessary to have an uninterrupted surface on which the car contact may travel, so that special methods of hanging the wire have been devised.

Any flexible wire or cable freely suspended at two points, and supporting its own weight alone, will assume a definite curve, known as the *catenary*. The equation of this curve is ordinarily stated as

$$y = \frac{a}{2}\left(e^{\frac{x}{a}} + e^{-\frac{x}{a}}\right) \qquad (1)$$

or in terms of hyperbolic functions

$$y = a \cosh \frac{x}{a} \tag{2}$$

where x and y are the coördinates of any point on the curve, referred to axes as shown in Fig. 159, a is a constant depending on the length of span and the sag in the wire, and e is the base of the natural system of logarithms. The length of span being L, and the supports at the same level, equation (1) becomes

$$a + D = \frac{a}{2}\left(e^{\frac{L}{2a}} + e^{-\frac{L}{2a}}\right) \tag{3}$$

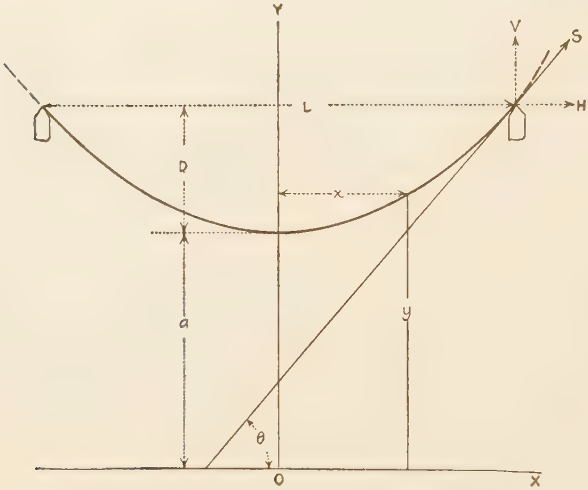

FIG. 159.—Equation of freely suspended wire.

or, from equation (2)

$$a + D = a \cosh \frac{L}{2a} \tag{4}$$

The corresponding length of arc, C, is

$$C = a\left(e^{\frac{L}{2a}} - e^{-\frac{L}{2a}}\right) \tag{5}$$

or

$$C = 2a \sinh \frac{L}{2a} \tag{6}$$

Knowing the length of arc and the deflection, the constant a may be determined by the following equation:

$$a = \frac{\left(\frac{C}{2}\right)^2 - D^2}{2D} \tag{7}$$

If only the length of span and the deflection are known, the constant a must be determined by means of successive assumptions and approximations.

The stress in the direction of the curve at any point, S, and its horizontal and vertical components, H and V, may be determined as follows: the only vertical stress must of necessity be that of the weight of one-half the total wire. If the weight of the wire per unit length be W, then

$$V = \frac{CW}{2} \tag{8}$$

and from the parallelogram of forces,

$$H = \frac{V}{\tan\theta} = aW \tag{9}$$

and

$$S = \frac{V}{\sin\theta} = (a + D)\,W \tag{10}$$

A solution of the above equations for a 4–0 wire and a span of 100 ft., with different values of a, is given in the following table:

STRESSES IN A 4–0 WIRE, 100-FT. SPAN

Constant, feet, a	Sag, feet, D	Length arc, feet, C	Total stress in lb. along direction of wire (S)	
			At center of span = H	At supports = S
25	69.05	181.34	16.0	60.24
50	27.15	117.52	32.0	49.42
100	12.76	104.22	64.0	72.22
200	6.28	101.04	128.1	132.12
400	3.13	100.26	256.2	258.20
600	2.08	100.116	384.3	385.64
1000	1.25	100.041	640.5	641.30
2000	0.625	100.010	1281.0	1281.40
4000	0.311	100.003	2562.0	2562.18
8000	0.156	100.001	5124.0	5124.10

Temperature affects the curve in which the wire hangs by changing its length. For a given length of wire at any temperature, that at another temperature may be found by the relation

$$l_t = l_o\,[1 + \alpha\,(t - t_o)] \tag{11}$$

where l_o is the length at any temperature t_o, l_t that at another temperature t, and α the linear coefficient of expansion of the wire.

In the case of a wire carrying a coating of ice or snow, equations (4), (5) and (6) may be used by changing the value of W to include the weight of added load per unit of length.

The above equations will give accurately the relations existing in any suspended wire carrying its own weight alone, as in the case of a transmission line or a simple trolley wire. It may be noted that to keep the sag down to values permissible for contact lines the tension must be considerable. If the sags are too small during hot weather, they may reduce to such a point when the temperature falls as to strain the wire.

As an example, consider a 4–0 hard-drawn copper trolley wire strung at a temperature of 100° F. with a sag of 2.08 ft. The tension at the supports, as given by the table, is 385.64 lb., which is but a moderate load on a wire of this cross-section. If the thermometer should drop to 23° below zero, a temperature not infrequently met with in our northern states, the length of the wire, determined by equation (11), is 100.001, which gives a stress of 5124.1 lb. at the supports. This is about the elastic limit for hard-drawn copper, and there is danger of stretching the wire. If there were any considerable ice load occurring at the same time, the strain might reach the breaking point.

Catenary Suspension.—An attempt to obviate this condition, which renders high-speed operation difficult in hot weather on account of the excessive sag, has been successfully made by the use of the so-called "catenary" suspension (Fig. 160). This consists in supporting the contact line frequently from an auxiliary or messenger wire, usually a steel cable of high tensile strength. The trolley wire is thus divided into a number of short spans, in which the sag can be reduced to a value which will not interfere with high-speed operation of the trains.

A wire or flexible cord, uniformly loaded along its horizontal projection, will assume the curve of a parabola. This curve differs but slightly from the catenary when the sag is comparatively small, so that the combination of messenger and contact wire may be considered as though the former were uniformly loaded along the horizontal, without introducing an appreciable error. The approximate deflection of a wire, calculated by this method, is

$$D = \frac{WL^2}{8H} \tag{12}$$

the values of D, W, L and H being the same as in equations (1) to (10). The length of a conductor having a given deflection is

$$C = L\left(1 + \frac{8D^2}{3L^2}\right) \tag{13}$$

By the application of these equations, it is possible to determine the deflection of the messenger cable at any point of the span, and construct a set of hangers of such lengths that the contact wire may be maintained horizontal at all points of support.

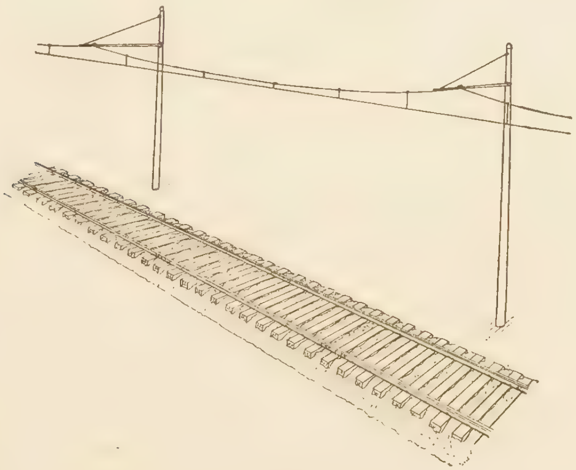

FIG. 160.—Catenary suspension.

The contact wire is not carried directly, but is suspended from a series of hangers attached to a messenger wire supported on the brackets.

The use of the catenary suspension makes possible a material lengthening of the span without increasing the sag of the contact wire; indeed, with a properly designed set of hangers, the length of span may be determined by entirely different considerations than the sag. An important point to note is that variations of temperature have a minimum effect on the level of the contact line. A reduction in temperature tends to decrease the sag of the messenger wire, but at the same time it shortens the hangers in proportion to their original lengths. The longest hangers are those adjacent to the supports, in which location the decrease in the sag is least. By adjusting the tension in the

messenger cable for an average point, it is possible to reduce the variations in height of the trolley wire at any other temperature to a minimum, although the entire contact line will rise somewhat in cold weather, and fall in hot weather.

A wide variation exists in the number of hangers employed with the catenary construction. In some of the early installations, as many as fifteen to nineteen were used for a single span of from 150 to 300 ft. Experience has shown that such a number of hangers is excessive, and that a material reduction can be made without affecting the general results of employing this type of suspension. But in a few instances, the desire to get a minimum cost has led the designers to cut down the number of suspension points to where the advantage of the construction has been largely eliminated. For example, a few installations have been made with three suspension points for a 150-ft. pole spacing. This makes the effective span of the contact wire 50 ft., or about half that used with the ordinary bracket construction, and the length between hangers is too great to secure a level wire. The principal advantage remaining with this minimum number of hangers is that the support is flexible, instead of rigid as with plain bracket suspension. In modern catenary construction, the number of hangers for a 150-ft. span is from five to nine, depending on the speed of the equipment and type of collector used.

Methods of Supporting Wires.—There are, in general, two methods of supporting the contact line: the span wire and the side- or center-bracket. The former construction, shown in Fig. 161, consists of a double row of poles carrying steel or iron cables placed transversely to the track. The contact line is suspended from insulators attached to these cross wires. The construction is equally suited to single or double track, the only difference being in the distance between the poles and the corresponding length of the span. This arrangement gives a fairly flexible support for the contact wire, and minimizes the pounding at the insulators due to the passage of the collectors on the moving cars.

Bracket construction consists essentially of a single line of poles, on each of which is placed a cross arm carrying an insulator. The arrangement may be adapted equally well for single or for double track. For the latter the poles are placed on the center line, between the tracks. The bracket construction is somewhat cheaper than the span wire, but has not the same flexibility.

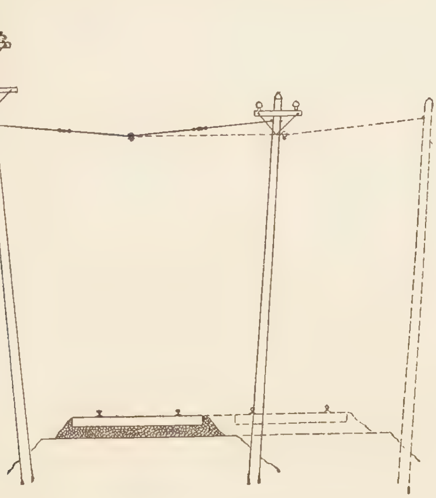

Fig. 161.—Span wire construction.

The construction is useful for either single or double track, using the arrangement shown in the full and in the dotted lines, respectively.

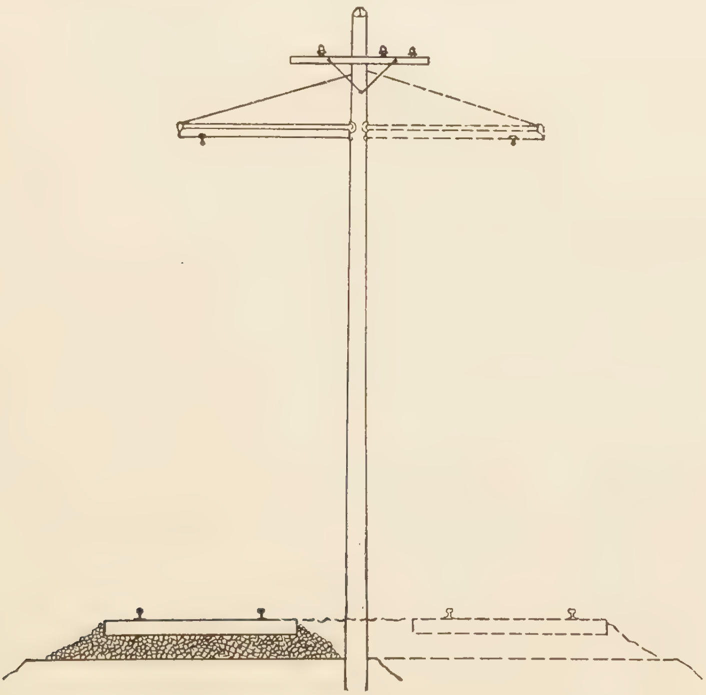

Fig. 162.—Center bracket construction.

This construction is equally well suited for single track, omitting the portions shown in dotted lines.

There is a tendency for the collectors of the cars or locomotives passing beneath to deliver a hammer blow at each point of suspension. This type is shown in Fig. 162 for a double-track road. For a single track, the bracket on one side is omitted, the rest of the construction remaining the same.

Either the bracket or the span wire readily lends itself to the catenary suspension. The messenger cable is hung from the bracket or from the span wire, and the contact line is attached to the messenger by hangers of suitable lengths. Since enough flexibility is secured by the catenary suspension, the disadvantages of the bracket construction disappear; and on account of its lower first cost it is the type usually employed for single-track or double-track roads. If a greater number of tracks are equipped, the span wire is cheaper. In some cases where there are many tracks, as in a yard, a cross-catenary suspension is used to keep the span wire level, thereby insuring that all of the contact lines are the same distance from the ground.

Use of Supporting Bridges.—For heavy work, as in railroad electrifications, a more permanent form of support has been used. The original construction of the New York, New Haven and Hartford consists of light bridges built of structural steel, placed approximately 300 ft. apart, and carrying the trolley wire from a double catenary. The latter consists of two messenger cables, arranged to form an equilateral triangle with the contact wire, which is at the bottom. Each point of support of the trolley wire is hung from both suspension cables, and these are kept the proper distance apart by a spacer. The wear on the original trolley wire was so great that it was decided to install an auxiliary contact conductor beneath the copper one. This new contact line is of steel, and is connected to the copper wire at points midway between the main hangers. By this means an extreme flexibility in the vertical plane is obtained, combined with considerable rigidity in the horizontal direction.

The double catenary suspension has been found better than the requirements of the heaviest trunk-line service demand. The later construction of the New Haven, and that of other main lines, has been made with a single catenary, light steel poles or bridges being used for support.

Size of Contact Conductor.—The proper size of the contact line may be determined from electrical relations; but it is important

to have it of sufficient section to withstand the mechanical strains which are imposed on it. For interurban construction, the most used size of contact conductor for overhead trolley lines is 4–0 wire, while for city construction 2–0 is quite often used. The odd sizes of wire, 0 and 3–0, are but rarely employed. The use of wire for the contact line involves some method of support which will not interfere with the smooth operation of the collecting device. When the ordinary round section of wire is employed, it is necessary to hold the wire by ears partially surrounding it. This causes "hard spots," sometimes resulting in damage to the overhead construction after long periods of use. Various non-circular sections of wire have been used from time to time; but the

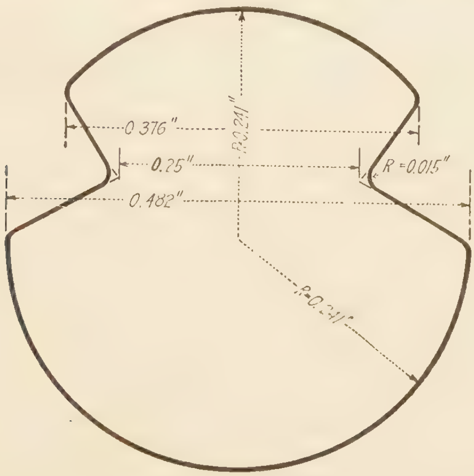

FIG. 163.—Standard 4–0 grooved trolley wire.

This is standard with the American Electric Railway Engineering Association. Other sizes are of similar section.

only one which has met with wide adoption is the grooved type, as that shown in Fig. 163, which represents a section of the standard 4–0 grooved wire adopted by the American Electric Railway Engineering Association. The cross-section of other sizes is similar in shape. This type of wire is held by ears which grip it in the grooves, and therefore offer no obstruction to the movement of the collector. It is used extensively in interurban and in city construction.

The Third Rail.—In cases where large amounts of current must be collected, especially at high speeds, the overhead trolley has

not been found entirely satisfactory. Part of this is due to the restricted area of contact between the moving collector and the wire, and the remainder to the inequalities of the surface caused by the variation in height of the wire. For such roads the use of the so-called "third rail" gives better results. This is essentially a steel conductor supported on insulators contiguous to and parallel with the track. In most cases it is placed at one side of and a few inches above the running rails. Occasionally it is located on the center line of the track, and still more infrequently is suspended above the track in a position similar to that of the ordinary trolley wire. These latter dispositions of the third rail are quite rare, and are adopted to meet special conditions. In the following paragraphs the location of the rail at one side of the track is the only one considered. There are two "types" of third rail in use, according to the location of the contact surface.

Over-Running Third Rail.—The older form of third rail construction, and the one most commonly used, is that in which

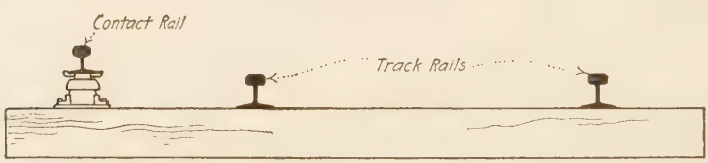

Fig. 164.—Unprotected over-running third rail.
This construction is used on all the elevated roads; the exact position of the contact rail varies somewhat.

the contact surface is the top of the rail. In this type of construction, Fig. 164, the rail is mounted on insulators of porcelain, reconstructed granite, or other suitable material. An ordinary rail section is most often employed, although in a few cases special designs have been used to reduce the cost of manufacture and to give a rail more readily mounted.

Many persons look on the third rail as a source of danger, due to the possibility of accidental contact from persons working along the track. To prevent such occurrence, it has become customary to "protect" the rail by making the metal inaccessible. At the same time, the contact surface must be kept free for the passage of the collector. It is quite difficult to effectively protect the third rail where the top contact is used. A number of devices, such as the mounting of boards parallel to the rail, at one side and above it, have been tried with indifferent success. Forms of

protection are shown in Fig. 165. A trouble with the unprotected rail is that it is liable to have a thin coat of ice form over its contact surface during sleet storms. This film, although sometimes very thin, is a good insulator, and occasionally prevents train movements entirely. Various methods have been tried to combat the difficulty. Some roads use steel scrapers attached to the trucks, passing over the rail surface ahead of the contact shoes. Others spray the rail with an ice-resisting liquid, such as

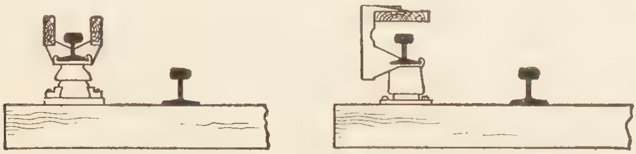

FIG. 165.—Forms of protection for over-running third rail.
These are used to prevent accidental contact of persons walking along the track with the live conductor.

salt or calcium chloride solution. The first expedient is not entirely successful, and the second may affect the insulation.

Under-Running Third Rail.—In order to more completely protect the third rail, and at the same time to lessen trouble from snow and sleet, the under-running contact has come into use in the last few years. The rail is suspended from hangers, as shown in Fig. 166, with insulation at the supports. It is a simple matter to protect against ordinary accidents by cover-

FIG. 166.—Under-running third-rail construction.

ing the top surface with a wooden trough, or with a special clay tile. Sleet does not form so easily on the under surface of the rail, and little or no trouble has been experienced from this source. The principal objection to the under-running third rail is that it encroaches more on the clearance limits of ordinary rolling stock; so that, unless special care is taken to eliminate cars having parts outside the clearance limits, fouling will result, with consequent interruption of service.

In some cases rails of the same chemical composition as the track rails are employed; but frequently they are made of a special composition selected to give maximum conductivity. The principal point is to have a soft steel, with a minimum amount of impurity. Such a composition would be too soft for a running rail, but its conductivity can be increased from one-third to one-half above that of the rail steel; and its hardness is sufficient to stand the wear that is produced by the rubbing of the contact

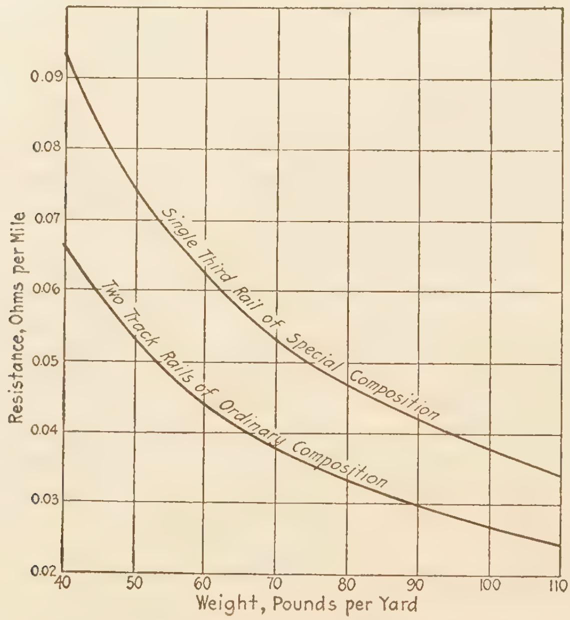

FIG. 167.—Resistance of rails with bonds.

shoes on its surface. The resistance of rails, complete with bonds, is shown in Fig. 167.

With the third rail, the conductivity, even for comparatively light cross-sections, is so great that little additional feeding capacity is needed, except on very heavy systems.

Underground Conduit Systems.—In a few cities, the opposition to the overhead trolley for esthetic reasons has been so great that it has been absolutely prohibited. In the United States the only instances are New York and Washington. In these cities it has been necessary to furnish electric street railway service without the use of overhead construction. The third rail, as

ordinarily used, is of course out of the question for use on city streets. Two alternatives remain: to place the conductors underground, contact being made through a slotted conduit, or else by a system of surface contact. Both have been tried, but the former has been used to the entire exclusion of the other.

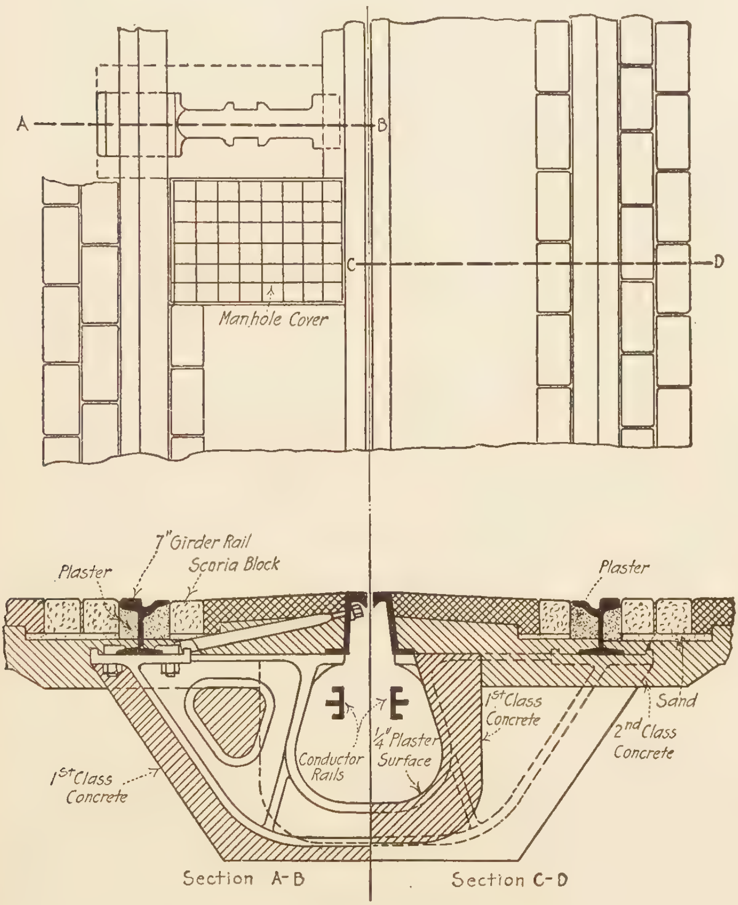

FIG. 168.—Underground conduit system.

In the underground conduit system, as installed in the two cities named, the conductors are placed in a continuous trough or conduit, as shown in Fig. 168. They consist of two T-rails, one positive and one negative, the track not being used for a conductor. These rails are entirely insulated from the ground by

porcelain insulators. Connection is made to the car equipment through a detachable plow, which is carried on one of the trucks, and has on its lower end a pair of shoes making contact with the two conductor rails. This system has given excellent service where it is used, both in the United States and abroad; the principal objection is the very high cost of installation.

Surface Contact Systems.—From time to time, experiments have been made with systems of current supply which do not depend on overhead wires, and are less expensive to install than the underground conduit. These "surface contact" systems all operate by having a series of contact studs, insulated from the ground, but placed practically flush with the street surface. These studs are normally not in the feeder circuit; but may be connected by a series of magnetic or of mechanical switches, operated automatically by the passage of a car in such a manner that only those studs under it are energized. Current is collected by some form of shoe or "skate" of metal connected to the car, and rubbing on the contact studs.

Owing to the great difficulty of maintaining the insulation of the studs, and keeping in operation a large number of automatic switches, the failure of any one of which will either leave the car stalled or else allow a live contact to remain unprotected, the systems of this type have never been popular. Although there are a few lines of surface contact road in operation, its use is not being extended; and in nearly all of the places where it has been tried it has been abandoned in favor of the overhead trolley or of the underground conduit system.

The Return Circuit.—In a constant potential circuit, the electrical relations are the same on either side of the line. When the system is ungrounded, the conductors may be made the same in cross-section, and the drop in potential will be evenly distributed. This is the case with the double-trolley construction, which is used in a few places in this country and abroad, and in the underground conduit system as installed in New York and Washington. In these the outgoing and the return circuits are made identical, and the losses are evenly divided on the two sides. There is no reason, save for convenience, why they should be thus distributed.

Use of Rails as a Conductor.—In any railway, it is necessary to use rails of iron or steel for the track. Even in the lightest section, these form an excellent conductor if properly connected

together, and, if there is no objection to operation on a grounded circuit, furnish a simple means of obtaining one of the main conductors of the electric system. The contact between the rail and the electrical apparatus on the car is universally made through the wheels, the motors and other equipment being grounded to the axles. In this way a moving contact at least equal to that between the contact line and the collecting device can be maintained without expense.

Track Bonding.—In order to utilize the track for one of the main conductors, it is necessary that a complete electric circuit be maintained through it. Although ordinary track, when newly laid, may be a fairly good conductor, it deteriorates rapidly through rusting at the rail joints, and the resistance becomes so high that the loss is excessive. To prevent this condition arising, it is customary to make a permanent electrical connection between the ends of each pair of abutting rails. This process is known as "bonding" the track.

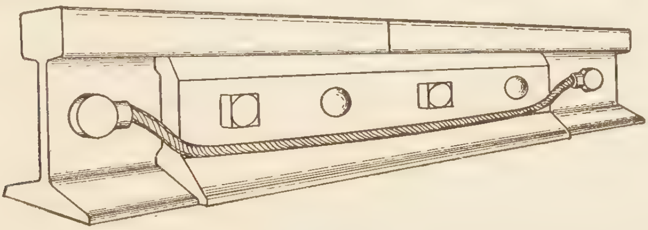

FIG. 169.—Chicago type unprotected rail bond.

The early electric roads were operated without bonding, until it was found that the power stations could not supply enough energy to properly drive the cars. On discovering the cause, bonds of iron wire of light section were used; but these did not make the track resistance low enough for successful operation. They have been superseded by bonds of copper wire or flexible strap, permanently fastened to the rails. The simplest type of bond in use consists of a piece of heavy copper wire, riveted through holes drilled in the rails far enough from the ends to make the connection outside the splice bars. This type of bond is fairly satisfactory, but in practice it has been found better to use a special terminal on the wire, as shown in Fig. 169, which can be expanded into the holes in the rails, instead of riveted. This makes a better mechanical connection, and prevents the entrance

of water into the junction, so that there is less liability of rusting and deterioration of the bond. Bonds of this type are open to a serious commercial objection, in that they are a constant temptation to copper thieves. To prevent this trouble, bonds are more frequently installed beneath the splice bars, where they are protected. A bond of this type is shown in Fig. 170.

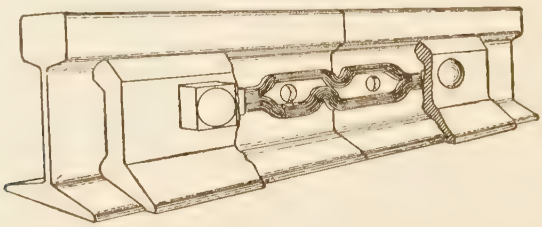

Fig. 170.—Protected rail bond.

A type which has been used to some extent is the soldered bond. This is held to the rail by soft soldering, so that no drilling is required. It is difficult to solder coppper to steel, and there is always danger of imperfect joints, which will break after a short period. On this account it has not been very popular.

A method of bonding which has met with considerable favor is to weld the bond terminals directly to the rails, by a method like

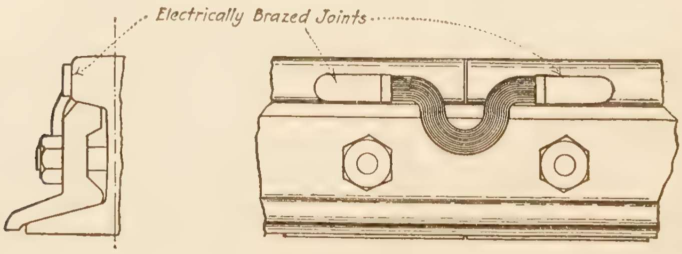

Fig. 171.—Electrically welded bond.

The soldered type bond is precisely similar in appearance; the difference is that the joints between the rail and the bond are made with soft solder.

that used for resistance welding of track. The equipment is almost identical, but is of smaller capacity. The connection is very similar to a brazed joint, and can be made entirely permanent if care is used. This type of bond (Fig. 171) is not subject to deterioration as with the expanded terminal type. It is somewhat more expensive to install; and, like the track weld, must be done by special machinery. If a bond fails after the welding

equipment has been removed replacement is difficult; otherwise it is exceedingly satisfactory.

Resistance of the Return Circuit.—When the track is used as the return circuit, it is important to know its electrical qualities. Ordinary steel has a conductivity of about one-twelfth that of copper, so that a rail weighing 100 lb. per yd. has a resistance of about 0.05 ohms per mile; and, since there are two rails which may be placed in parallel in each track, the total per mile is 0.025 ohms. To this must be added the resistance of the bonds. These are about equivalent in section to a 4–0 copper wire, but there is a certain additional loss in the contact between steel and copper. While the total resistance of bonds varies greatly, being least for the welded type, it may ordinarily be taken as about 0.005 ohms per mile of single rail, with joints every 30 ft. This makes the total resistance per mile of single track, laid with 100-lb. rails, about 0.0275 ohms. For other weights of rail, the values will be proportional, except that the effect of the bonds is constant. The resistance of the two rails of a track, with ordinary bonding, as a function of the weight, is shown in Fig. 167. In case the bonding is not well maintained, the track resistance may be materially greater.

Reactance of Rails.—When alternating current is employed for the propulsion of trains, the track being used for the return conductor, an additional effect is noticed. There is an extra drop in the circuit due to the reactance of the rails. These, being of a magnetic material, have a relatively high inductance, and also cause "skin effect" even with fairly low frequencies. The values which have been obtained in tests on the flow of alternating current in rails are not entirely satisfactory, although a great deal of experimental data has been taken. The best results published are probably those of the Electric Railway Test Commission.[1] The reactance changes with the current carried, due largely to variations in permeability. In any case the "apparent resistance" (impedance) is several times the true resistance of the rail when transmitting direct current.

Defects in the Return Circuit.—The conductivity of good track is so high that there is a comparatively small drop in potential in carrying the current. In a single track with 100-lb. rails this is but 2.75 volts per mile per 100 amp. With this value,

[1] *Report of the Electric Railway Test Commission,* Chapter VI, p. 387; McGraw Publishing Co., New York, 1906.

it is evident that very little, if any, additional feeder capacity is required unless the load is exceedingly large. But if there are a few bad bonds in the track, all the current may be forced to flow through one rail, thus increasing the drop. To obviate this difficulty, it is customary to cross-bond the rails at frequent intervals by connecting jumpers to them, as shown in Fig. 172. With this arrangement the distance the current will have to flow through one rail alone is limited to the portion between cross-bonds containing the bad connection; and, if there are several open bonds in the track, the chances of its electrical continuity being broken are very much reduced.

The result of increased resistance of the track circuit is seen at once in the greater loss. The value of the energy may be measured in dollars and cents; and only a little calculation is needed to show that it is financially the proper thing to keep the return circuit in first-class condition.

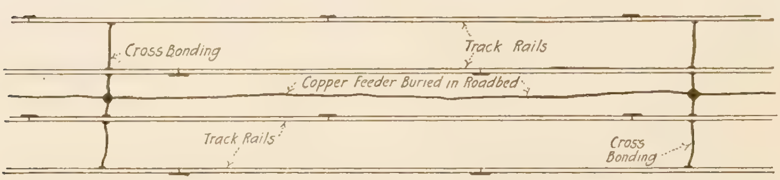

FIG. 172.—Cross bonding with return feeder.

Electrolysis.—There is another disadvantage from having a high resistance, which is even more serious, and which cannot be directly measured in the money cost. This is the damage to property caused by electrolytic action. The track is normally partially insulated from the earth, especially in dry weather; but it must be considered as a grounded circuit at all times. Since the track is in connection with the soil, either partially or completely, the latter becomes an electric conductor in parallel with the rails. Its resistance is high, but not enough so to prevent some current flowing through it. If this can be determined, it is possible to calculate the proportion of the current which will flow through the ground; but local conditions vary so greatly that it is difficult to compute it accurately. The use of the earth as a conductor in parallel with the track is not inherently a disadvantage, since the effect is to increase the conductivity of the return circuit; but the difficulty lies in controlling the path of the current as it flows through the ground.

Earth conduction is electrolytic in its nature. The soil consists of inert matter, holding a certain proportion of metallic salts which may be in solid form, and a content of water, more or less impregnated with solutions of salts. When current enters the earth, the effect is to eat away the metal; and where it leaves the ground, a metal or hydrogen will be deposited. If the earth circuit were made up of an iron salt, the effect would be to dissolve a certain amount of iron from the rail at the point where the current enters the ground, and to deposit an equal quantity of iron where the current leaves. This would result in a certain weight of metal being worn away from the rails at definite points, which, although a serious matter, concerns no one but the railroad company. The deposition of metal on the rail at another place would have but little effect, since it could not aid the rail section to any extent.

The main difficulty with earth conduction is that in cities there are many lines of pipe and cable running parallel with the railway tracks, buried beneath the paving of the streets through which the tracks run. Such lines furnish a conducting medium which is superior to the earth; and the effect is for the current to be diverted to them whenever there is any tendency for it to leave the rails. A pipe line lying parallel to the track increases the ability to take current from the rails in proportion to its conductivity, so that the tendency to have current flow through outside paths is increased greatly by the presence of such conductors. When the current does flow through them, the same phenomena occur as when it leaves the rail. At the point where the current enters the conductor there is a deposit, usually of hydrogen, and where it leaves, the metal is eaten away. The amount which will be eaten is a function of the current and the time. One ampere, flowing continuously for a year, will dissolve 13.4 lb. of iron in the ferric state (trivalent), 20.1 lb. of ferrous (bivalent) iron, or 74.5 lb. of lead. Corrosion is likely to take place to a greater extent than indicated by these values, since the electrolytic action will induce natural corrosion by the salts in the soil. The effect is rendered more serious since the tendency is for the current to cause deep pits in the metal, sometimes eating through pipes in a few spots when the remainder of the surface is but slightly affected.

Remedies for Electrolysis.—Since the track is earthed, and the ground furnishes a path in parallel with the rails, it is not

possible to entirely eliminate electrolytic action so long as they are employed for a conductor. The only absolute preventive is to use an insulated return circuit. In that case electrolysis cannot exist. But the excellence of the track as an electric conductor makes it most desirable to employ it for conducting the current. There are several methods for mitigating the effects of electrolysis, while at the same time permitting the use of the rails as part of the electric circuit.

The simplest way of preventing electrolysis is to cover the parallel lines of pipe and other conductors with a protective coating, which, if it could be thoroughly applied, and be permanent, would be a most effective remedy. Unfortunately, it is not possible to commercially cover pipe with a perfect coating; and, even if a proper coat could be made, it would be subject to deterioration in contact with the soil. The general method of failure of such a form of protection is by its breaking in a few places. This has the effect of localizing the electrolysis, causing more rapid destruction at such points than if no coating were used.

Another method which has been advocated to some extent is to break the pipe into sections by the use of insulated joints. This makes it a much poorer conductor than otherwise. With this arrangement, the current has a tendency to follow the pipe as far as it is a continuous conductor, and to pass into the earth around the insulated joint and back into the pipe, thus causing electrolytic action at such points. These joints are somewhat expensive, and this method of protection is only good in combination with others.

Since the current inherently seeks the best conductor, and hence tends to follow a pipe line, an effective remedy should be to make the pipe as good a conductor as possible, by bonding the joints, and attaching it to the rail at suitable points. This is often referred to as the "pipe drainage system." This makes the pipe line an integral part of the electric circuit, and eliminates the chance of electrolytic conduction. It leads to much greater currents in the pipes than when no connection is used, and may have injurious effects if, for any reason, a bond is broken. In such an event the electrolysis is locally much worse than if no remedy is used.

The effectiveness of the pipe drainage system is considerably improved if a series of negative feeders is installed to aid the

rails. This tends to remove the injurious action when a single bond is defective, and to reduce the drop of potential in general, as shown in Fig. 173. In any case it is difficult to determine the proper feeder capacity, since the entire circuit is grounded, and the calculation of the drop through parallel circuits is involved.

In order to have this method of protection effective, all pipes which are in the immediate vicinity of the railway track must be connected to it, and must be electrically continuous. If this is done, there is some additional danger to other pipes which are not connected to the return system.

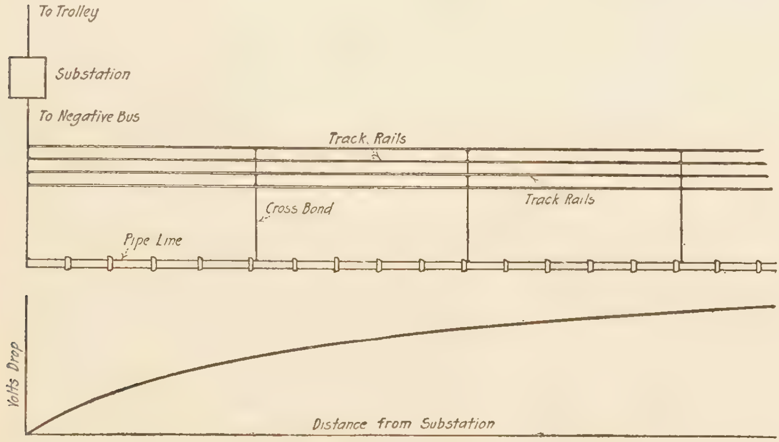

FIG. 173.—Potential drop with pipe drainage system.
This arrangement is used for prevention of electrolysis in a number of large city systems.

It is evident that any method of protection which reduces to a minimum the difference of potential between points in the track will lessen the tendency for current to flow in paths exterior to the regular circuit. Such a condition can be obtained by the use of insulated track feeders, proportioned in a manner similar to the feeding system for the distributing circuit. If the number and resistances of such feeders be properly chosen, the difference of potential between various points can be reduced to any desired value. In order to have such systems effective, the feeders must be entirely insulated from the rails except at the points of connection. In certain cases, if the track is tied to the generator at the station with a short, low-resistance cable, it may be necessary to use feeders to other parts of the

system which are larger than warranted by the economics of the situation. This may be obviated by removing the direct connection at the station entirely, or by increasing its resistance until the desired effect is obtained (see Fig. 174). If some of the feeders are long, boosters may be inserted, as is sometimes done in the distributing circuit.

All of the above methods have been used for the mitigation of electrolysis. At the present time there is no general agreement that one is decidedly better than the others. The two which have been used to the greatest extent are pipe drainage and

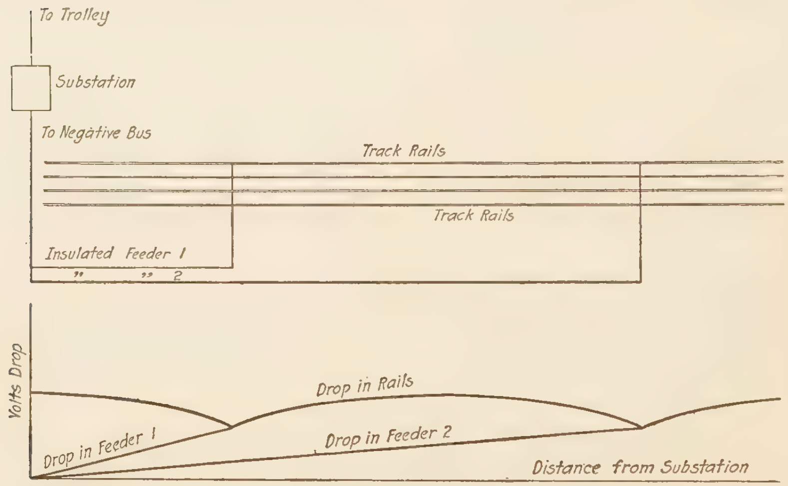

Fig. 174.—Potential drop with insulated negative feeders of correct resistance.

This method of electrolysis mitigation is recommended by the United States Bureau of Standards.

the insulated feeder system. A possible solution is the combination of these two.

Polarity of the Direct-Current Circuit.—Until now nothing definite has been said about the proper direction of current flow in direct-current railway systems. So far as electrolytic effects go, either the positive or the negative terminal of the generator may be connected to the distributing circuit; for, if any current goes out of the rails, it must return at some other point; and it is where the current leaves the metallic conductor that the destructive effect occurs. There is this difference: if the distributing circuit is connected to the positive terminal of the generator, the electrolysis of the rail will occur at the point farthest from

the station, and of the pipes or other structures nearest it; while if the distributing circuit is connected to the negative pole, the pipes will be attacked farthest from the station and the rails will be affected at the point near it. Apparently, since the amount of metal dissolved is a function of the current, there is no inherent difference in the two methods of connection. Experience has shown, however, that the current flow to or from the rail at the points far from the station will be distributed over a considerable distance, while nearby it will be concentrated in a short space. Since electrolysis of the rail only affects the railway company, it is the pipe line which must be protected; and it is easier to inspect a short length of pipe in the vicinity of the station, and renew it when necessary, than to take care of a long section at an indefinite distance. For this reason, all electric railways have for many years adopted the practice of making the rail circuit negative, thus localizing the damage. With a better understanding of the causes and results of electrolysis, more effective remedies have been developed, so that the need for keeping the same polarity is less; but in the intervening time the practice has been so standardized that it is in universal use where direct current is employed for train propulsion.

Alternating Currents and Electrolysis.—The above discussion on electrolysis has been confined to a consideration of the effects of direct currents. A number of experiments have been conducted to determine whether similar results are obtained when alternating currents are used for train propulsion with a grounded return. Up to date the indications of such tests have been negative, there being no evidence that any electrolysis results from the alternating-current circuit. This would naturally be the case since the reversal of the current is so rapid that, even if metal should be dissolved in one alternation, it would be replaced on the electrode during the succeeding half cycle.

Natural Corrosion.—In making tests to determine the exact amount of electrolytic corrosion it is difficult to obtain accurate results. Any practical tests must necessarily mean leaving metal plates in the soil, exposed to the action of the electric current. Under such conditions there is invariably some action due to the natural corrosion of the metal in contact with the earth salts. Some recent tests[1] indicate that the rate of corrosion under such

[1] E. M. Scofield and L. A. Stenger: "Corrosion of Metals in Natural Soils," *Electric Railway Journal*, Vol. XLIV, p. 1092, Nov. 14, 1914.

circumstances is much greater than was formerly imagined. Corrosion may be due to impurities in the metals in contact with the soil. Different soils have diverse activities in corroding metals; and sometimes when two kinds of soil are in contact with a single piece of metal the corrosion is increased over that in a homogeneous earth. The corrosion noted in some tests is sufficient to explain fully all the phenomena observed in connection with what is supposed to be electrolysis from current passing through metals in contact with the earth.

Special Methods of Feeding.—At various times, special methods of feeding have been suggested, and some of them have been used in a few cases. A favorite suggestion in the early days of electric railway history was to use the two contact wires of a double-track road as the two outside lines of a three-wire system, the track being the neutral. The arrangement of circuits is

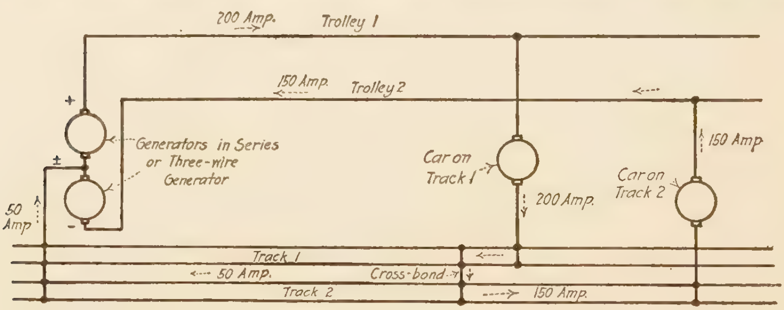

Fig. 175.—Three-wire distribution system.

In this system the two trolley wires are made the opposite sides of the circuit, and the track the neutral. Note that the current flowing through the track is considerably smaller than that in the trolley wires.

shown in Fig. 175. By this means the current flowing in the track would be reduced to that necessary for supplying the unbalance of the system, and electrolytic effects would be eliminated.

In a three-wire system, the neutral carries but a small current, and hence its size *may* be much less than that of the outside wires. The effect of making the rail the neutral is to almost entirely lose the advantage of its high conductivity as an aid to the distributing circuit, so that the decrease in the amount of copper required over the two-wire system with grounded return is quite small. The extra complication of the contact conductors, requiring those of opposite polarity to be insulated from each other, makes crossings and switches difficult to lay out, and necessitates the use of

special insulators. Further, it makes the connection of all the overhead lines into a single network impossible, and may prevent the operation of a damaged section by feeding from adjacent parts of the circuit.

The use of higher working potentials has been advocated for many years, and there has been a notable advance in this respect. The first electric railways were operated on 100 volts, or thereabouts; from that time a rapid increase was made until 450 volts was used on the Richmond road in 1888. That potential was adopted as being the highest for which a practical direct-current generator could be built. Since that time the increase has been slower, but the pressure has gradually been brought up to 600 volts, which is now almost a universal standard. In some few instances roads have been built for pressures from 650 to 750 volts, which, until a few years ago, represented the limit of commutator design.

Quite recently, the possibility of using two or more commutators in series has been exploited in the so-called "1200-volt" system, which in its original conception contemplated the use of two standard railway motors, insulated for the higher potential, connected permanently in series on a 1200-volt circuit. The generating equipment similarly consisted of two standard 600-volt machines in series. The effect of this increase of line potential is to reduce the amount of distribution copper for the same loss in inverse proportion to the square of the potential; so that for two lines of equal capacity, one for 1200 volts would require but one-fourth as much copper in the distributing circuit as the other at 600 volts. Better knowledge of commutation and the use of interpole machines has made possible the construction of motors and generators carrying 1200 volts on a single commutator, so that the apparatus has been simplified. Further than this, it has allowed the placing of two of these machines in series on a 2400-volt circuit.

Further increases in the contact line potential depend on the development of motors adapted to commutate high pressures. It is interesting to note that the most recent installation, that of the Chicago, Milwaukee and St. Paul, contemplates the use of two direct-current motors in series on a trolley at a potential of 3000 volts. Laboratory tests involving the use of still higher potentials show that such increases are within the limits of possibility.

When alternating current is used on the contact line, there is no definite limit to the pressure that can be employed, for lowering transformers give any desired potential for the operation of the equipment. The limit is then only in the pressure for which the contact line and the collectors can be insulated. Pressures of 11,000 volts to 20,000 volts are now being used, but there is no reason why they should not be increased if found desirable.

CHAPTER XIII

SUBSTATIONS FOR ELECTRIC RAILWAYS

Historical Sketch of Development.—Early electric railways had the simplest of electrical circuits. The generators produced directly the e.m.f. required for operating the car motors, and fed into the contact line, usually without the aid of an auxiliary feeder system. This arrangement has the sole advantage of simplicity. In every other respect it is deficient. With the growth of electric railways, it was soon found that the limitations imposed by this arrangement were serious. At the outset, the efficiency of the distribution became low, on account of the excessive fall of potential in the contact line. The obvious remedy was to increase the area of the conductor, but this has the effect of augmenting the fixed charges on the investment. In the larger systems, an attempt was made to improve the economy without excessive cost of distribution copper by using a number of independent power stations, located at such points as would cut down the length of circuit fed from any one of them to a minimum. While this made a decided improvement in the economy of the system, the result was to have a number of small and relatively inefficient plants, each operating at a low load factor. Various arrangements to better this condition were tried, such as the use of boosters on long feeders; but these remedies did not get to the root of the trouble.

The beneficial effects on the distribution circuit of the use of higher potentials was early demonstrated; but it was not found possible to increase the capacity of a single commutator beyond a limiting e.m.f of about 550 to 650 volts. This was (and still is, for some classes of railway service) the maximum potential that could be applied successfully to the contact line. The difficulties of distribution were found greatest in interurban roads, where the length of feeder circuits and the concentration of the load in a few scattered units made the problem exceedingly difficult to handle. In order to get away from the limitations imposed by direct generation at the contact line potential, the

use of a separate generating and transmission system working at a pressure considerably higher than that of the distribution circuit was tried fairly early in the history of electric railways. This furnished a solution of the problem which has been entirely satisfactory except for the complications involved, and is now universally used for most classes of electric railways.

Complex Distribution Systems.—The use of a high-tension transmission circuit with a low-tension distribution system requires the introduction of some form of transforming machinery into the electric circuit, resulting in a great flexibility not possible with direct generation. Generally speaking, there are four possible combinations which may be made, as follows:

1. Generation of alternating current, and distribution as alternating current at the same frequency.
2. Generation of direct current, and distribution as alternating current.
3. Generation of direct current, and distribution as direct current.
4. Generation of alternating current, and distribution as direct current.

Of these four possible combinations, all except the first require the use of some form of rotating converting machinery (with the exception of the mercury vapor rectifier). The use of the first combination is limited to those roads using alternating-current equipment on the cars and locomotives, and for this class of service is almost universally employed.

The second and the third methods contemplate the use of high-tension direct-current transmission. At the present time there is but one system available for this form of transmission, the Thury system. This consists of the use of a number of constant-current machines in series, both at the generating and at the receiving ends of the transmission line. The motors at the receiving station drive ordinary generators of the constant-potential type, designed for the distributing circuits on which they are to operate. In Europe, several transmission lines of considerable length, and working at maximum potentials of over 50,000 volts, are in service. The system is extremely simple, but is limited in application on account of its lack of flexibility. The second combination would be available for the operation of alternating-current roads, but on account of the

ability to employ stationary transformers in the first method, that is invariably used in practice. The third combination is rarely seen.

The fourth method of transmission is the one of widest application, since it allows the use of standard alternating-current machinery for the transmission circuit, and standard direct-current apparatus on the distributing system. The conversion from alternating current to direct can be made in a number of ways, as explained in this chapter.

Types of Converters.—At the present time, there are several methods available for the conversion of alternating current into direct current. They are:

1. The motor–generator set.
   (a) Using a synchronous motor.
   (b) Using an induction motor.
2. The synchronous (rotary) converter.
3. The induction motor–converter.
4. The permutator.
5. The mercury vapor rectifier.
6. Various types of mechanical rectifiers.

The motor–generator set, the motor–converter, and the permutator, give direct-current potentials which are independent of the alternating e.m.f. The alternating-current winding may be constructed for any desired potential within the limits of the machine insulation, while the direct-current side is arranged to give any standard potential desired. The synchronous converter, the mercury vapor rectifier, and all the types of mechanical rectifiers, are limited in their design to a fixed ratio between alternating and direct e.m.f.'s. The latter must therefore be used in connection with lowering transformers to give the desired direct potential.

Motor–Generator Sets.—The simplest and most flexible type of converting machinery is the motor–generator with an induction motor, shown diagrammatically in Fig. 176. The two machines are mounted with their rotating members on a common shaft, but are in all other respects independent. The induction motor is usually of the squirrel-cage type, since the starting duty is not heavy; and it operates at high efficiency and practically constant speed over the entire range of load. The direct-current generator may be of any standard type, and wound

for the contact line potential. It can be equipped with a shunt or a compound field winding; and constant potential regulation may be effected either by the compounding of the series field or by the use of an automatic regulator.

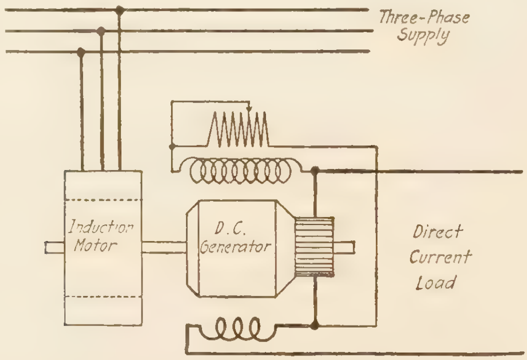

Fig. 176.—Induction motor–generator set.

In some cases a shunt-wound generator, with a potential regulator, may be used instead of the compound-wound generator illustrated.

The objections to the induction motor–generator are chiefly its high first cost, low efficiency as compared with other forms of converters, and the comparatively large lagging current which is taken by the induction motor.

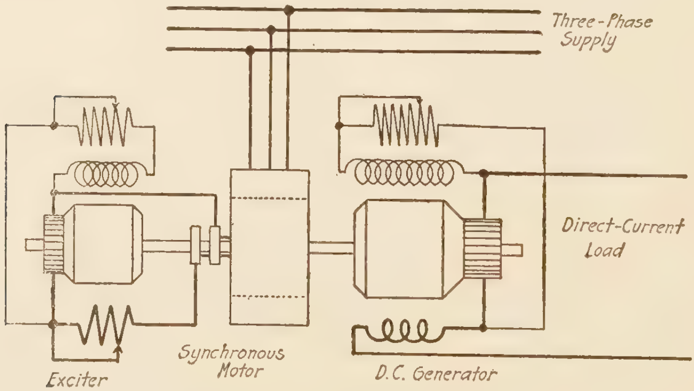

Fig. 177.—Synchronous motor–generator set.

The synchronous motor is occasionally excited from the direct-current generator when a supply of direct current is available for starting, or when a self-starting motor is used.

The synchronous motor–generator, shown in Fig. 177, removes the objection of low power factor, which is inherent to the induction motor. Exciting current is most frequently taken from

a separate direct-current generator, usually mounted on the same shaft with the main machines, although in some cases direct current from the main generator is used for excitation. By varying the exciting current the power factor may be controlled within certain limits. The cost, weight and efficiency are approximately the same as for the induction motor-generator.

Synchronous Converters.—The synchronous converter, in effect, combines the armatures of the two machines of the synchronous motor-generator set. By so doing, the e.m.f. obtained at the brushes is a fixed function of that led into the machine from the alternating-current side, making independent regulation of the direct-current pressure impossible. Various devices may be introduced to remedy this defect, the simplest of which is the use of a series-wound synchronous booster, through which the alternating current must pass. By exciting the field of the booster with the line current of the direct-current side, an additional e.m.f. is added to or subtracted from the potential delivered by the transformers. Another method of regulation is the use of the split-pole converter, in which the ratio between alternating and direct e.m.f.'s may be varied by changing the wave from within the converter armature. Neither scheme is used in practice to any extent for railway service, but they are valuable in connection with industrial applications.

The usual method of regulation is to put a series winding on the converter field, as shown in Fig. 178, similar to the ordinary series field winding used on compound direct-current generators. In connection with such a winding reactance coils, through which the main current is drawn, are placed on the alternating-current side. The shunt field rheostat is set so that the converter draws slightly lagging current at no load. With increase in load, the series turns of the field winding cause over-excitation, making the current lead the e.m.f. When this leading current is drawn through the inductance of the machine, the transformers and the reactance coils, a reactive drop is produced which *adds* to the potential delivered from the circuit. By properly proportioning the series winding and the reactance coils, the potential on the direct-current side may be regulated.

In large systems, where too much leading current is objectionable, the e.m.f. supplied the alternating side of the rotary converter is varied by some standard form of potential regulator, such as the induction regulator. This method may be used alone, or in

combination with the series winding on the converter; so that both the direct e.m.f. and the power factor of the alternating-current circuit may be governed at will. The arrangement is similar to that shown in Fig. 178, except that the regulator replaces the reactance coils.

The early rotary converters were all built for comparatively low frequencies, most of them being for 25 cycles. Recent improvements in design, especially the use of interpoles, have made the performance and the cost of 60-cycle synchronous converters practically on a par with those for lower frequencies.

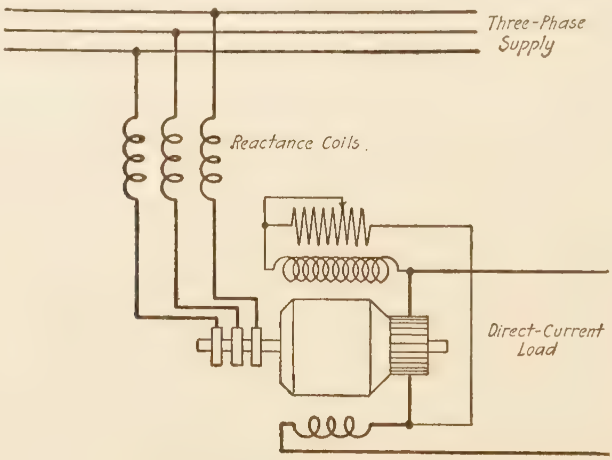

FIG. 178.—Synchronous converter with regulating reactance. The reactance coils may be replaced with an automatic potential regulator.

The Motor-Converter.—The motor-converter, or "cascade-converter," is an application of the same principle as that used in cascade control of induction motors. It consists, Fig. 179, of a primary winding like that for an induction motor, and a secondary of a type similar to that of the phase-wound motor, the principal difference being that the converter is ordinarily designed for a larger number of phases. The secondary winding is tapped directly into the armature of a machine electrically the same as the synchronous converter. As in cascade operation of motors, the motor end and the converter end of the set may each have any number of poles; practically they are wound for the same number. For starting, the secondary winding of the induction machine is brought out to collector rings, through which it may be short-circuited with resistance.

In operation, the set runs at half the speed of the primary field, the frequency in the secondary being half that of the line; while the converter operates as though in synchronism at the secondary frequency. Half of the power is transmitted directly through the secondary winding, while the other half is delivered through the shaft. The size of the set is therefore decidedly less than for a motor–generator of equal rating. The efficiency is considerably better than that of a motor–generator, but slightly less than of the ordinary rotary converter. Synchronizing is extremely simple, consisting in adjusting the starting resistance until the machine falls into step. The starting current is small; but, on the other hand, the magnetizing current is drawn directly from the line, as in an induction motor, so that the power factor

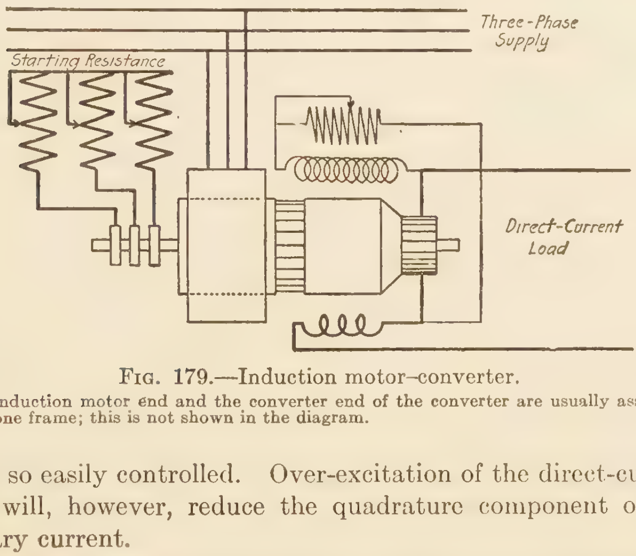

Fig. 179.—Induction motor–converter.

The induction motor end and the converter end of the converter are usually assembled within one frame; this is not shown in the diagram.

is not so easily controlled. Over-excitation of the direct-current field will, however, reduce the quadrature component of the primary current.

While the motor–converter had, at the time of its introduction, considerable superiority over the synchronous converter for operation at high frequencies, recent improvements in the latter have placed the two machines about on a par in this respect. When the motor–converter can have its primary wound for the line potential, without the use of lowering transformers, there is little difference in first cost; when transformers are required, the motor–converter will be more expensive. Its greatest advantage is the small amount of attention needed for operation, as compared with the synchronous converter.

The Permutator.—If the secondary winding of an induction motor is held still, current will be generated in it at the frequency of the primary circuit, and at an e.m.f. equal to that of the primary, multiplied by the ratio of transformation. If the secondary winding be connected to a commutator of the ordinary type, and a set of brushes rotated thereon *at synchronous speed*, direct current can be taken off and used for any purpose. A machine embodying this principle, known as the permutator, has been used for several years in Europe for converting alternating current into direct. In its construction, the parts may be arranged similarly to those of the induction motor; but, since there is no relative motion between them, no air-gap is necessary, and by omitting it the magnetizing current is reduced. Brushes are rotated on the commutator by means of a small synchronous motor wound with the same number of poles as the main machine.

The permutator is reported to have excellent operating characteristics. The efficiency is high, since the mechanical losses due to rotation are almost entirely absent; and the weight and cost are about the same as those of rotary converters of the same rating. The principal objection is due to rotation of the brushes. This makes necessary a somewhat complicated brush rigging, and precludes any repairs or replacement of brushes while the machine is in operation. The magnetizing current, being the same in character as that for the induction motor, is lagging; and, notwithstanding the quadrature component is less than for a motor of equal rating, it is never possible to eliminate it, although the power factor is very high. The ratio between the alternating and the direct e.m.f. is fixed in any one machine, but is not limited to a definite ratio as with the synchronous converter. It is possible to wind the machine for high potentials, as with the induction motor or the motor-converter. With the improvement of other forms of converters, it is doubtful whether the permutator will have a wide application.

The Mercury Vapor Rectifier.—The use of the mercury vapor rectifier, in connection with locomotive equipment, has already been mentioned in Chapter V. This apparatus is equally applicable for substation service. The principle of operation is based on the fact, discovered by Dr. Peter Cooper Hewitt, that a mercury electrode in contact with the vapor of mercury will conduct current in one direction only.

To utilize the principle for rectification from a single-phase circuit, the terminals of the secondary winding of a transformer (or of an auto-transformer) are connected to two electrodes in a vessel containing a mercury cathode, and vapor of mercury at the proper pressure. The arrangement of circuits is shown in Fig. 180. There is no tendency to cause a flow of current through the vapor under such conditions; but when the current is once started, as may be done by providing a metallic conductor between the electrodes (for instance, by tilting the container until the mercury forms a continuous film between the cathode and

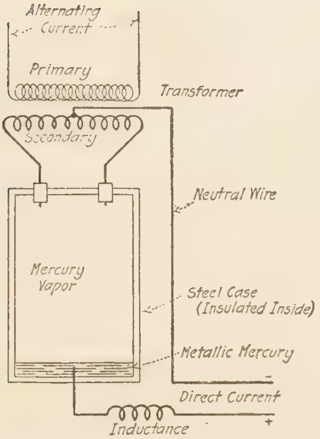

Fig. 180.—Single-phase mercury vapor rectifier.

The direct potential may be varied by connecting to different taps on the transformer secondary.

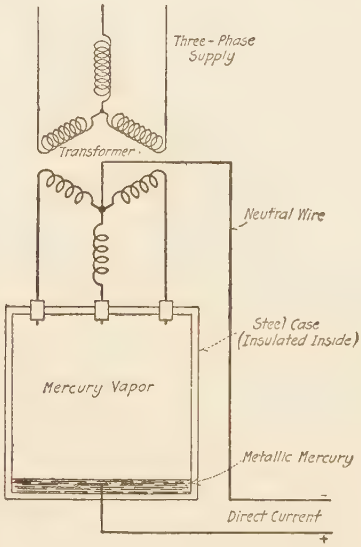

Fig. 181.—Three-phase mercury vapor rectifier.

the other electrode), or by means of a motor-generator set, the vapor will continue to conduct current from the anode (electrode connected to the transformer winding) to the cathode as long as the e.m.f. persists in the same direction. When it ceases, the vapor becomes a non-conductor. If, however, current continues to flow until the e.m.f. has established itself in the proper direction through the other electrode connected to the transformer, the current will be maintained through the vapor in the same direction as before, but from the other anode. With a

single-phase source, this can be done if sufficient inductance is inserted in the receiving circuit. If the latter is normally inductive, as when supplying motors, no additional reactance is needed. The other lead for the direct current is taken from the neutral point of the transformer; and hence the current flows for one-half of the alternating cycle through one portion, and for the other half through the remainder, of the winding.

With a three-phase supply for the alternating current, the arrangement is slightly different, as shown in Fig. 181. There is no need of inductance to maintain the circuit through the vapor, since two currents are always flowing in the same direction.

Although the current produced by the rectifier is unidirectional, it is not uniform in amplitude. If there were no inductance in the circuit, the form of the rectified current would be very nearly the same as that of the alternating, with every other half-wave reversed. The effect of inductance is to smooth out the waves of current until there is only a slight ripple. For similar reasons, the current produced from a polyphase rectifier is more uniform than when a single phase is used. Extensive tests which have been made indicate that the effect of inductance on the wave form is great enough that standard direct-current motors will give entirely satisfactory service.

The efficiency of the rectifier is high at commercial potentials. The loss appears to consist mainly of a definite drop which is independent of the current; so that the converter has a constant efficiency at all loads. This drop of potential varies from approximately 14 volts in the small rectifiers used for charging storage batteries, up to 50 volts in some of the larger units which have been tested. The rectifier used on the Pennsylvania Railroad experimental equipment in 1914[1] showed a constant drop of about 25 volts, when delivering approximately 1200 volts direct current. The efficiency is hence in the neighborhood of 98 per cent.

It must be remembered that at the present time (1915) the mercury vapor rectifier is still in the experimental state, but apparatus has been built giving outputs as high as 1000 kw. and 7000 volts.[2] Compared with other forms of converting machinery, it is light in weight, low in first cost and in maintenance, and exceptionally high in efficiency. If the development proceeds as rapidly as is at present anticipated, it will certainly place the

[1] *Electric Railway Journal*, Dec. 19, 1914, Vol. XLIV, p. 1343.

[2] *Electric Journal*, January, 1915, Vol. XII, p. 2.

rectifier in an excellent position, both for operation on locomotives or cars, and for permanent location in substations along the line.

Mechanical Rectifiers.—Some work has been done in perfecting various forms of mechanical rectifiers. These devices are practically two-part commutators, driven at synchronous speed, the brushes being placed in such positions that they will reverse the current as the alternating wave is passing through zero. If the current and inductance remain constant, such a device can be made very satisfactory. If, however, the apparent inductance of the direct-current circuit is subject to rapid fluctuations, the position of the wave will shift; and, to secure good commutation, the brushes should be moved correspondingly. This makes the operation of the rectifier unsatisfactory in connection with a motor load. Various attempts to overcome the trouble have been made, and results of tests have been announced from time to time which would indicate that satisfactory rectifiers have been built; but up to the present none has been used commercially with any large measure of success. It is questionable whether any device of this type can equal the performance of the mercury-vapor rectifier, especially at high potentials and large currents.

Comparison of Converters.—In the present state of the art, it is exceedingly difficult to give a satisfactory comparison of the different forms of apparatus for converting alternating current into direct. The excellence of the modern synchronous converter has caused its adoption for practically all classes of railway service, so that motor–generator sets, the induction motor–converter, and the permutator may not be used to any extent in competition with it. On the other hand, the synchronous converter, from its inherent design, is difficult to construct for the extremely high direct potentials which apparently will be necessary for future development of heavy railway equipment if direct-current motors are to be employed; and the possibilities of rectifiers, especially of the mercury vapor type, are so attractive that the latter will undoubtedly be a serious competitor of the synchronous converter in this field. It is, therefore, idle to consider converting equipment standardized at the present time; although, where heavy currents at comparatively low potentials are required, the synchronous converter is undoubtedly the best machine at present.

Substation Equipment.—With the wide diversity in apparatus which may be used for converting one kind of current into another, it is not possible to consider any form of substation equipment as standard. The arrangement of apparatus, using synchronous converters, has, however, been almost completely standardized. What is desired, in order to keep the operating cost low, is a station in which the machinery is most nearly automatic, so that little or no attention is necessary. With modern machines, this is approximated; but with rotating devices, there is always need for expert attention.

There is one notable exception: the alternating-current transformer station. If alternating current is to be used on the contact line, all the equipment that is required in the substation is the necessary installation of transformers, with proper switching and protective devices. Such a station can be made automatic in operation, requiring no attention whatever after the line switches have been closed, except in case of abnormal conditions. If the mercury vapor converter is developed, as now seems likely, it may be possible to have similar automatic substations for conversion from alternating to direct current.

Storage Batteries in Substations.—The widely fluctuating loads in ordinary railway service make it impossible to keep the machines operating at the most efficient load at all times. There are two types of fluctuation of load: the regular daily changes, due to the number of trains in operation, and momentary variations from trains starting, ascending grades, etc. The former can be easily taken care of by having the proper number of units in operation, starting and stopping them as the load changes. The latter cannot be cared for in this manner, but will place momentary overloads on the equipment, sometimes amounting to twice the full-load rating of the machines in service.

By the use of storage batteries, these rapid momentary fluctuations can be smoothed out to a very large extent on roads operating with direct current. For such service the battery is either "floated" on the line, or connected to it through a suitable regulator. A sudden demand for current causes the battery to discharge, so that the additional load is assumed by it instead of by the converters. When the load falls below the average value, the batteries are charged. In this way the substation equipment is kept operating at or near its maximum efficiency, and the regulation of the transmission circuit is improved.

The other principal use of storage batteries in substations is to assume a portion of the total load, so that the excess capacity need not be carried in rotating machines. This has the effect of reducing the cost of the transmission line and of the generating equipment, since the peak is carried by the batteries, and does not affect the power station.

A third use of the storage battery is to assume the total load when, for any reason, the generating equipment is out of service. This makes it possible to operate the road for short periods in case of accident to the machinery, so that the damaged apparatus may sometimes be repaired and put back in service before the battery is discharged. The battery may also assume the entire load during hours when the service is light, as at night.

It is evident that the same battery can be used to serve all of these purposes; but the capacity required is very different for each of them. To smooth out the momentary variations in load, a comparatively small battery is needed, since the total time of charge and discharge is quite short for a single peak due to starting a car. To assume the daily overloads during the rush hours a larger battery is needed, and to assume the entire load of the station for extended periods takes a still larger battery, the exact size of course depending on the frequency and length of the interruptions to be provided for.

It cannot be claimed that the operation of storage batteries is in itself efficient, for the conversion from electric into chemical energy and back again will result in a considerable loss. The efficiency in this service will ordinarily be from 75 to 85 per cent. The effectiveness of the battery comes from equalization of the load, so that the generators, transmission and converters operate with less loss.

The use of batteries is not so general at present as it was several years ago. Better design of electrical machinery makes it more able to stand the momentary overloads; and the efficiency of modern equipment is high over the entire range of loads. The main functions of the battery may thus be served by other means, so that there is not the use for it that formerly obtained.

Batteries can be applied to alternating-current roads with the interposition of a rotary converter or a motor–generator to connect them to the load. While this arrangement is not widely used, there is at least one installation in the United States operating in this manner. It is reported to be entirely satisfactory.

Classes of Distribution Systems.—Distribution circuits may be classed into two radically different forms: those in which the substation may be located at the center of the system, the lines radiating from it; and those in which the distribution is linear, there being but one line, along which the substation may be located. The former represents the conditions in city service, or in some kinds of terminal electrification; while the latter represents the case of the interurban road or the trunk line. Naturally, there will be many places in which the two classes will overlap, so that an absolute classification is somewhat difficult. The general principle remains the same in either, and the problems involved are similar.

Location and Capacity of Substations.—The most difficult problem in connection with the distribution system is the determination of the proper positions for substations to give the maximum efficiency in operation. The problem is complicated by the fact that the location not only affects the amount of feeder copper required for a given efficiency, or the efficiency with a given amount of copper, but also changes the capacity of individual stations, thus influencing the cost. What is desired from the economic standpoint is to determine that arrangement which will give the lowest annual cost for losses, and interest and depreciation on the investment.

The most general statement of the proper arrangement of the circuit is that known as Kelvin's law, which was developed by Lord Kelvin in connection with the determination of conductor size for transmission circuits. This law is usually stated as follows: "The most economical conductor is that in which the annual cost of energy wasted (due to line loss) is equal to the interest and depreciation on the capital outlay that is proportional to the weight of the conductor."

In practice it is not possible to have the conditions of Kelvin's law met at all times. The law holds true, in its strictest sense, only when a given value of current is flowing constantly. It has been seen that the current in an electric railway transmission or distribution circuit is always fluctuating over a wide range. The condition necessary for use in connection with Kelvin's law may be determined for all practical purposes by taking the root mean square value over an extended period of time, which will correctly represent the average loss due to the current, as called for in the statement of the law.

In the case of roads which are of the radial type, the location of substations is comparatively simple, although the mathematical treatment is much involved. What is required is to have efficient operation, at the same time keeping the maximum drop as small as possible consistent with economy. In such cases, the amount of load is ordinarily sufficiently great that the capacity of a single substation will be large enough to utilize machinery in units that may be operated at or near maximum efficiency. In other words, just enough units may be in service at any one time that the load on each machine is very near its full-load rating.[1] In roads of this type the load is naturally concentrated at a few points. Practically all lines in this class are city systems, or congested parts of trunk lines such as terminals and yards. The substations may therefore be placed at the normal centers of load. In case there is a question of the exact location, it may be determined by assuming the average load at the mean distance on each radial line fed from the station, and finding the electrical center of gravity of the total load.

Location of City Substations.—The location of substations for city lines is affected to a large extent by the high cost of land at the normal centers of load. For this reason the largest roads have found it economical to concentrate as much capacity in a single station as possible without excessive drop on any of the outlying lines. This concentration has been carried to such a point that synchronous converters of extremely large rating have been built; and in some cases converters of such sizes as 4000 kw. have been constructed to replace units of 1500 kw., the better knowledge of design enabling manufacturers to produce machines of the larger size which can actually replace the smaller units on the same foundations.[2]

Location of Substations for Interurban Roads.—Interurban roads fall into the class of linear distribution, and generally can be treated in a much simpler manner than city lines. The variation in the number of substations carries with it a considerable difference in the cost of equipment, as well as in that of operation. The total capacity of all the substations must be equal to that of

[1] The effect of the proper operation of the individual units on the all-day efficiency of the substation is shown in a paper by L. P. Crecelius, *Electric Journal*, October, 1914, Vol. XI, p. 543.

[2] "History of the Rotary Converter in America," F. D. Newbury, *Electric Journal*, January, 1915, Vol. XII, p. 27.

the generating station, augmented by whatever reserve equipment is required due to uneven distribution of the load. As the number of substations is increased, the number and total capacity of such reserve units will become greater. Conversely, as the number of stations is decreased, the size of each unit which can be economically employed will be greater, resulting in less cost of equipment. The cost of ground and building will not vary much with the capacity of the station, nor will the attendance; so that a very decided gain can be made from greater spacing. The cost of attendance will also be very nearly constant, no matter what the capacity.

Generally, the fixed charges representing the investment in land, buildings and equipment, and the cost of operation, will increase as a function of the number of substations; while the fixed charges on the secondary copper, and the value of the loss in the distribution circuit, vary inversely with it. It should, therefore, be possible to find a condition where the total cost will be a minimum, corresponding to a definite spacing.

Two methods of determining the proper spacing of substations have been suggested: the first, calculation of the distance by trial for any particular case,[1] and the second, by an analysis of the variables, with a mathematical solution.[2] It is the opinion of engineers that the exact location of substations cannot be made entirely by mathematical treatment, since the variables which may enter will vitiate the results to a considerable extent. For instance, on interurban roads using direct current, it is necessary to have an attendant at the substation at all times. His duties will not occupy the entire day, so that it is usual to place the substations so far as possible in towns located along the line. The operator may then also perform the duties of freight- and ticket-agent, thus calling for a smaller number of employees, or giving better service, than would otherwise be possible. This practice is nearly universal with interurban roads.

Effect of Potential on Substation Spacing.—Since the loss in the distributing circuit varies as the square of the pressure, it is evident that the most economical potential is the highest which

[1] "Some Considerations Determining the Location of Electric Railway Substations," C. W. Ricker, *Transactions* A. I. E. E., Vol. XXIV (1905), p. 1097.

[2] "The Determination of the Economic Location of Substations in Electric Railways," Gerard B. Werner, *Transactions* A. I. E. E., Vol. XXVII, (1908), p. 1201.

can be practically employed. As has been stated in previous chapters, direct-current motors have been standardized for 600 volts and multiples of this value. If the pressure is increased from 600 volts to 1200 volts on the contact line, the losses in the distribution circuit, for the same amount of copper, will be but one-fourth what they are at the lower potential. On the other hand, with the same loss, the conductor will have but one-fourth the section and hence cost but one-fourth as much. There is another important advantage which can be obtained by the use of higher potentials. The economical distance between substations can be considerably greater with the same total operating cost. This will result in practically doubling the distance between stations. It also has the effect of increasing the capacity of each substation, so that the investment in reserve equipment can be less and the operating efficiency higher.

The excellent results of the increase of potential on the efficiency of the distribution system have led many interurban roads to adopt higher working pressures than the old standard of 600 volts. It has already been mentioned that the connection of two 600-volt motors in series permits operation on a 1200-volt system, the only difference being that the motors must be insulated for a higher pressure, and the control equipment must be changed accordingly. The advance in the manufacture of railway apparatus has made feasible the construction of motors using 1200 volts on a single commutator, and two such machines may be placed in series on a 2400-volt circuit. In one proposed installation, the pressure per commutator is to be increased to 1500 volts, making a distribution potential of 3000 volts. No definite limit is in sight for direct current. If the mercury vapor converter fulfils expectations, the limiting feature will be the commutating capacity of direct-current motors.

Alternating-Current Distribution.—The advantage of high trolley potential is the one main feature which has led to the alternating-current system. In this case there is no limit to the distributing e.m.f., since stationary transformers along the track and on the cars and locomotives furnish a simple means of obtaining any pressure suitable for the apparatus and the transmission. Single-phase motors of the commutator type are all inherently low-potential machines; but the use of a transformer makes practical any pressure on the distributing circuit, so long as the insulation can be taken care of.

The use of stationary transformers removes nearly all the limitations from the operating economy of the converting apparatus, since the demand for attendance is reduced to a minimum. There is no need for elaborate controlling devices, as with the synchronous converter installations, and the no-load losses are so small that the equipment can be permanently connected for the maximum output. The greater potential possible makes concentration of the substation equipment feasible, giving higher load factors.

Portable Substations.—It is not possible to predetermine the load on a railway system under all conditions. The growth of traffic may be different from what was expected in the estimates, or there may be additional service required for portions of the year.

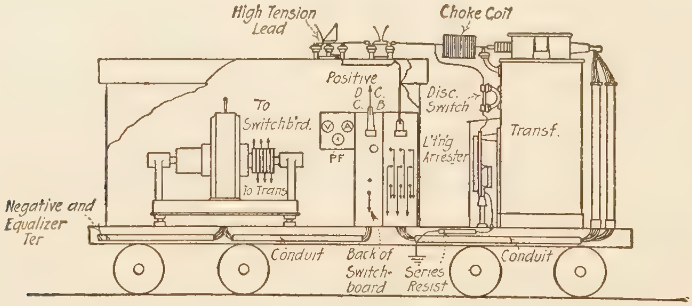

Fig. 182.—Portable substation.

As shown, an outdoor type transformer is used for lowering from the transmission line potential. In some designs, a transformer of the ordinary indoor type is used instead.

In such cases it is not desirable to permanently install sufficient substation equipment to meet the maximum demand, since it will be needed for but a few months in the year. On the other hand, operation with too small substation capacity is unsatisfactory, due to the large drop in potential, to say nothing of the excessive loss. In recent years, many interurban roads have adopted the method of using portable substations, which may be moved from point to point as needed. While developed for the purposes mentioned, the portable substation is useful when building a new line or an extension, in which case the transmission line may be installed, the permanent converting equipment being left until the required capacity and the correct location have been determined. It is also useful when repairs have to be made on an existing station, for the portable substation can be placed on a siding near the

permanent one, which may be entirely disconnected while repairs are being made.

For direct-current roads, the converting equipment will consist of a rotary converter of proper size, with suitable transformers and controlling devices. Such a station is shown diagrammatically in Fig. 182. The apparatus is placed on a specially designed car, the transformers being of the indoor or the outdoor type, as desired. No motive power equipment is used, the car being hauled by locomotives from point to point. Converter substations of this type are usually of 300 kw. capacity, although sometimes larger.

For alternating-current roads, all that is required is a transformer of the proper characteristics. This can usually be carried on a car and left at the proper location to aid or replace the permanent equipment. No special car is required in this case.

CHAPTER XIV

THE TRANSMISSION CIRCUIT

Development.—In the preceding chapters the characteristics of the distributing circuit have been considered largely apart from any connection with the transmission system. It is evident that the successful operation of an electric railway does not depend on the use of high-tension transmission with conversion to the proper kind of current for motor service; but the latter as generated may be entirely satisfactory, provided the amount of power to be delivered by one generating station is sufficient to warrant its operation at the potential of the distributing circuit. In most cases the amount of power which can be so concentrated is not enough to justify such an arrangement. The reason for this is entirely because of the economies which can be effected by the use of large generating systems.

Improvements in power-plant equipment, coupled with large increase in the commercial capacities of the units, are modifying conditions so that a system correctly laid out in the past with individual generating stations may now be considered inefficient beside a modern one with the power supply concentrated in a single plant. In fact, several large railroads have found it economical to abandon the older individual power stations, replacing them with single large plants and high-tension transmission with low-tension secondary distribution. The advantages of large generating units will be considered in the next chapter; for the present let it be assumed that such an arrangement is the most satisfactory for the ordinary railroad. It then becomes necessary to transmit the power so produced to the point where it is to be utilized with a minimum of loss; or, more strictly, in such a manner that the total cost of transmitting the energy will be least.

Types of Transmission Circuits.—As already shown, electric energy can be transmitted either by direct current or alternating current. The former is in many ways superior, since but a single pair of conductors is required, and the motors which can be used

on direct-current circuits are in some respects superior to alternating-current motors. Certain effects of the alternating current, such as inductance and capacity, which are present to a considerable extent in transmission lines, disappear with direct current. But the latter has one insurmountable disadvantage: up to the present time it is impossible to convert it from one potential to another without the use of rotating machinery; while, on the other hand, the transformer provides a simple and efficient means for doing this with alternating current. It is this one thing which has generally prohibited the use of direct current for long-distance transmission.

The only way in which direct current has been used for transmission is by the so-called "Thury" system, in which a constant current is employed at variable potential. This has already been referred to in the previous chapter. It requires the use of special rotating machinery at each end of the transmission line, and does not possess the flexibility of the constant potential system, so that its application has been exceedingly limited.

Alternating current is available at a number of commercial frequencies, and either single-phase or polyphase. It is shown in all text-books on electric transmission that the single-phase and two-phase circuits require a greater weight of conductor than the other polyphase systems; so that, unless there is some other compensating advantage, the first-mentioned forms of electric power are inferior to the others. The single-phase requires the simplest machinery, and only two wires are necessary for the electric circuits. It has the disadvantage of more expensive generating equipment; and the motors for operation on a single phase are not so satisfactory for general purposes as polyphase motors. Even when a single-phase contact line is to be employed, there are enough advantages in polyphase transmission that it is sometimes used in that connection.

When the distributing circuit is to be arranged for direct current, the use of polyphase transmission is universal, partly on account of the saving in cost of conductor and partly because of the superiority of the machinery. So far as transmission economy goes, the two-phase and the single-phase are on a par; but even though the latter requires four[1] wires against two for the former, it is preferable on account of the better operation of the

[1] Three-wire two-phase circuits are practically never used for transmission purposes, on account of the lack of symmetry.

equipment. The three-phase circuit, for the same transmission loss, requires but three-fourths as much conductor material as either the single-phase or the two-phase; and the machinery is at least as good as, and as cheap as, two-phase apparatus. For this reason the two-phase circuit has become practically obsolete for all kinds of electric transmission and distribution.

The arguments in favor of the three-phase circuit apply with equal force to higher numbers of phases; but these require additional wires without a corresponding gain in efficiency. It is true that a larger number increases the capacity of rotating machinery; but these advantages can be obtained with three-phase transmission by a simple arrangement of the raising and lowering transformers. For these reasons the higher polyphase circuits have never been used commercially for this purpose; and today, three-phase is universally adopted whenever transmission with polyphase circuits is desired.

Need for High Tension.—It has been shown that the loss in the electric circuit, for a given size of conductor and amount of power transmitted, varies inversely as the square of the potential. It is for this reason, and for this reason alone, that the use of high potential is needed for the economical transmission of power. This relation holds true, irrespective of the kind of current, phase or frequency. If there were no limitations, there would be no inherent objections to the use of extremely high potentials for all kinds of power transmission. Practically, the use of high-tension circuits brings a number of disadvantages which must be overcome to make them practical.

The most troublesome feature to be taken into account in the use of high tension is the requirement of properly insulating the conductors, both from each other and from the earth. The trouble from this cause is small at low pressures, but when the potential exceeds rather definite limits, the difficulties increase very rapidly. In addition to this, the effects of capacitance increase with the potential, so that special precautions must be taken to avoid difficulty from this source. Lightning also requires particular attention. It is interesting to note that when extremely high pressure lines are operated, the need for protection against surges due to short circuits or sudden opening of the switches exceeds that against lightning. In such cases lightning has been found to cause little or no disturbance on the line, and sometimes does not even interfere with the continuity of operation.

Choice of Potential.—The proper potential for the transmission circuit, as well as the size of conductor to be used, can be determined with some exactness by the application of well-known engineering principles. That potential should be used which will give the lowest total annual cost for wasted energy and interest and depreciation on the investment. This may be found by Kelvin's law, as in the case of the distributing circuit.

Other considerations often affect the result in the determination of the potential and size of conductor, so that the best values, as found theoretically, may not be the ones finally adopted. The use of standard equipment will generally dictate that the pressure adopted be one of a comparatively few for which apparatus is made commercially. This may effect a considerable reduction in first cost, which will overbalance possible saving in energy due to a higher potential. Again, many electric roads are now becoming interconnected through high-tension networks, and it may be better to use the existing potential of the network rather than to connect through transformers.

In certain cases the size of conductor, as determined for economy, may be less than that which can be used commercially on a long line. If no saving in cost of conductor is to be effected, there is no advantage in the use of an extremely high potential, since the difficulties in transmission increase with the pressure. The required regulation of the circuit may dictate a wire in excess of the most economical size.

A great many interurban roads in the Middle West have practically standardized on potentials of 16,500 and 33,000 volts for transmission systems. While these pressures are not high, according to modern standards, the amounts of power to be transmitted are not so large as to occasion excessive loss. As the size of the road increases, the need for higher potentials is more keenly felt, and a readjustment of the circuits may become necessary for the highest economy.

When purchasing transforming equipment, it is often possible to anticipate future changes in operating potential by having the transformers wound for a higher pressure than that on which they are used. This may be done by bringing out taps from intermediate points on the windings, by connecting the high-tension coils in parallel, or by arranging the primaries in delta. If it is desired to increase the transmission pressure, the transformers will then be ready for the change with no added cost save the work of rearranging the connections.

Regulation of the Transmission Line.—In all constant potential electric circuits, it is essential that the variation in pressure shall not exceed a certain amount, depending on the character of the apparatus connected to it. While the operation of electric cars and locomotives does not demand a very close regulation in the distributing circuit, the operation of the substation equipment and of the generators is affected injuriously by wide fluctuations in the transmission pressure. In addition to this, the power factor of the alternating-current circuit has a marked effect on the performance and on the line drop.

Some form of automatic regulation is very desirable to keep the potential of the transmission circuit at a nearly constant value. This may be obtained in direct-current circuits by compounding the generators, so that the e.m.f. produced will increase enough with load to compensate for the line drop. When alternating current is used, this method of regulation has never met with success, for it requires complication of the machines and does not give entirely satisfactory operation. When synchronous machinery, such as rotary converters, is used at the receiving end of the line, regulation may be effected by over-excitation, and drawing the current through reactance. This combination will cause the leading current taken on account of the over-excitation to produce a negative impedance drop, which has the effect of compounding the transmission line. Where the regulation must be closer than can be obtained with this arrangement, or where it is desirable to keep the power factor constant, automatic potential regulators can be used.

Close regulation is not a prime essential, so far as the successful operation of most types of railway motors is concerned. We have seen that the allowable drop is quite considerable, especially for interurban operation. But in general poor regulation usually carries with it low efficiency, so that the pressure should not be allowed to vary through such wide limits in the transmission line as in the distribution circuit. The total permissible drop must be divided between the different parts of the system, unless some form of automatic pressure control is employed. If synchronous converters are used without any form of regulator, the variation in potential is transmitted through the machines and the transformers directly, so that the drop in the transmission line will add to that in the distributing circuit. When an automatic regulator is employed, the drop in the two circuits can be made practically independent.

Mechanical Arrangements of Transmission Lines.—In many cases, the transmission line for an electric railway differs from that for general power purposes, mainly because the wire circuit can be placed on the same poles that carry the distributing feeders and furnish the support for the contact conductor. This cheapens the construction materially over that used for a separate line, since the only expense incurred above that for the transmission wire, insulators and cross-arms is due to the extra length of poles required for supporting the high-tension circuit. On account of this, it may in certain cases be cheaper to use a fairly low tension, rather than to adopt a type of insulator which will require a separate pole line for the transmission system.

These remarks, of course, do not apply to roads operating with the third rail, where any pole lines which may be erected are entirely for the transmission and the distribution circuits; nor where conditions are such that it is necessary to use underground conductors. In cities, the transmission line can ordinarily be made much more direct than to follow the railway track.

The high-tension circuit is usually run with copper wires of the proper size, but occasionally aluminum is employed instead. The relative merits of the two metals have been the subject of considerable discussion, and the final decision usually lies with the metal which is cheaper at the time of purchase. The fluctuations of the metal market are so rapid and so erratic that it is not possible to state definitely that the advantage lies with either.

In some cases a single transmission circuit is used alone; but in others, to avoid interruption of service, two or more are employed in parallel, either on the same pole line or on entirely separate structures. The choice depends largely on the conditions of operation. In climates where there are few periods of severe weather, the advantage of duplicate lines is much less than where storms are frequent and violent. This is a question which must be settled independently for each separate case.

The determination of mechanical stress in transmission lines can be accomplished by the same method as that given for the distribution circuit. Added load due to ice is of greater importance in this case, on account of the smaller size of conductor ordinarily used, and the longer spans which are often employed. The side strain caused by wind is also of considerable moment, especially when aluminum conductors are used.

CHAPTER XV

POWER GENERATION

Requirements.—The requirements of electric railways are in no material way different from those for other users of electric power. The load, it is true, is subject to wide fluctuations, but this can equally well be said of other consumers. There is, therefore, no inherent reason why the power plants for railway service should differ in any great respect from those for general power purposes.

Capacity of the Power Station.—After the capacities of the different substations have been determined, as indicated in previous chapters, similar calculations for the power plant are comparatively easy. The all-day load charts for the various substations should be superposed to give the total demand on the power plant. This is a process of summation, the instantaneous loads being added directly together. From the load chart for the power station, obtained in this manner, the total output may be found by integration, and the average load determined by dividing the energy output by the time used in the integration.

The size of individual units depends on the average load, and also on the momentary overload. Their number should be so chosen that, at any period of the day (except, perhaps, when the load is the very lightest), the machines in service will be working at or near full load. This consideration is important if the highest efficiency is to be reached in operation of the plant. In the smallest stations, where only two or three machines will be used, it is not possible to do more than approximate this condition; but in the larger systems, the number of units can be chosen with regard to economy in operation.

The efficiency of most electric generators is greatest at full load, or at an output slightly less than this point, although the variation in efficiency from half load to load-and-a-quarter is, in modern machines, quite small. Outside these limits, the efficiency falls off quite rapidly; and if generators are to be operated at light load for large portions of the day, the efficiency of the station may

be reduced materially. Proper choice of units will, therefore, be ineffective unless accompanied by correct operation.

A lower limit to the subdivision of the generators also exists. The cost of electrical machinery increases per kilowatt as the size of unit is decreased, and the maximum operating efficiency becomes lower. It is important that the units be as large as is consistent with proper subdivision of the load, that these advantages in cost and efficiency of the larger machines may be availed of. In any particular case, the proper selection of apparatus should be carefully considered. The possibility of future extensions to the system should not be overlooked, for this may influence to a considerable degree the selection of generating equipment.

Power Plant Location.—Abstractly considered, the location of the power plant may be determined in the same way as that of the substations. The center of load can be found, and the station may be built at this point. In general, such a situation will be at a place where it is impractical to build a power plant. For a successful steam plant, the location must be such that coal can be delivered cheaply and easily, and an adequate supply of water for the boilers and condensers must be available. The first consideration practically dictates that the station shall be situated on the line of a steam railroad, unless a suitable interchange agreement can be made for operating coal trains over the tracks of the electric road. Sometimes it is feasible to place the power plant on the bank of a navigable stream, in which case coal can often be delivered by water at a cost less than possible when rail delivery is used. The second consideration generally demands that the station be located on or near a river or creek of sufficient size for the water supply. In certain cases it may be cheaper to pipe water considerable distances; as, for example, to use a city water supply, and have some form of water cooling plant in connection with the condensing system. Local conditions affect these points so much that it is not possible to formulate any general rules for location.

The most important single thing which will affect the position of the plant, after these primary considerations, is the cost of land. This will practically prohibit the erection of a station in the center of a city, which would be, for example, the ideal place for it in connection with a street railway. It is frequently far cheaper in total operating cost to locate the station outside the

city where land is cheap, and where the advantages of coal and water supply may be better than in the more central position.

When power is to be transmitted to substations at high potential, the exact location of the plant has but a small effect on the total economy of the system. In such cases there is no great advantage in putting the station at the center of load, and it may be preferable to have it at a point far removed from the ideal position, if the other factors can be better met.

Hydraulic Power.—Where water power is available, it is always desirable to consider using this in place of steam. In order to compete with steam power, the total cost of generation with water power must be as small as, or smaller than, that for steam. The operating costs for hydro-electric plants are usually materially lower than those for steam stations; but the construction costs are so much higher that there is often little difference between the total annual expenses.

When hydraulic power is used, the location of the plant is, of course, the outcome of natural conditions, and cannot be changed materially. In cases where the hydro-electric development must be placed a long distance from the railroad system, the question may arise whether it would be cheaper to build a steam power plant nearer the center of load, thus doing away with a long transmission line. Such problems must be considered individually on their merits.

Choice of Equipment.—In the selection of power station machinery, there are many different types which may be used, and considerable engineering judgment is necessary to get the best combination for a particular installation. Aside from those for hydraulic power, the prime movers available are steam turbines, reciprocating steam engines, and internal combustion engines. The choice between them depends to a considerable extent on the size of the plant and the cost of fuel. With large units and fairly low prices for coal, the steam turbine is the most economical prime mover available. With smaller machines, the reciproctaing engine is not at such a great disadvantage. The field of the gas engine is rather uncertain, and it does not appear to be a serious competitor of steam for large sizes.

Power Plant Construction.—No attempt will be made to consider the actual design of power plants. For such information, reference should be made to any good book on power plant design. It should be noted that the type of plant will be influenced to some

extent by the cost of land available for the station. If it is necessary to build in the congested part of a city, where land is expensive, apparatus should be used which is of the greatest compactness. This consideration usually calls for the steam turbine in preference to other prime movers. In some cases an attempt has been made to still further reduce the ground required by placing the equipment in two stories. This arrangement has not been uniformly successful.

Purchased Power.—A movement has been put forward by the large central stations within the last few years to advocate the use of energy purchased from power companies for railroad operal tion. There are several reasons why this should be the ideaarrangement, and why the cost of energy to the railroad should be lower when purchased than when generated in the road's own plant. The power company is specifically in the business of producing and selling energy. The entire staff has been trained to that end; and better results should be obtained with such an organization than by that of a railroad, whose primary business is to furnish transportation. Coal and supplies should be bought at lower prices, both on account of the better organization, and on account of the larger amounts purchased.

A large central station generates such great amounts of energy that the railroad load is but a small portion of the total. It is possible to use more efficient prime movers and electric machinery than are available for the railroad alone. The larger size of the units, and the concentration of power in a single station, reduces the cost of producing energy by a not inconsiderable amount. But the greatest argument in favor of this method of operation is the "diversity factor." If the railroad load came at exactly the same time as the general demand, there would be no advantage in central station power, other than those mentioned. Experience shows, however, that the peaks of the various loads never coincide. For example, in a large city transportation is required in greatest amount at times immediately before the factories and offices open, and just after they close. Even a small diversity in time may make a great difference in the total capacity of generating equipment needed. If the railway peaks could be made to come during light load for other purposes, it might easily be possible that the entire railway service in a large city could be furnished by a central power plant with no addition to the equipment required for other users. This condition cannot be attained, for

some railway service is needed at the peak of the general power load, and the maximum railway load coincides very nearly with a large demand for power. But even a slight difference permits a considerable reduction in total plant capacity. Electrified steam roads handling large amounts of freight have found it possible to run many of the freight trains at night, when the general power demand is a minimum. In this way the maximum railway load may be kept entirely away from the industrial and lighting peaks, so that the best possible utilization of the power plant machinery may be realized.

It is this diversity feature which makes it feasible for the power companies to make such attractive prices for energy to railway companies. On the side of the railroad, it is easy to see that, if power can be purchased for what its generation in an independent plant would cost, and no investment is required, it forms a very good way of solving the problem. Even a large trunk line may find it profitable to buy power.

As an example of what can be done with purchased power, it may be stated that practically all energy for operation of the electric roads in Chicago, both surface and elevated, is generated in the stations of the Commonwealth Edison Company, and sold to the roads at a price so low that they have found it advantageous to shut down their own plants completely. Further than this, the substations are being operated by the power company, and power is distributed from a single station to several different roads. In this way the load factor of the substations is improved, and the total cost of equipment decreased, while the efficiency is raised. Equally good results might be obtained in other cities, both for the city roads, and for interurban lines entering them.

In this connection, it is only fair to state that many of the smaller central stations have been built to accommodate both the railway load and the lighting load, and have been so operated for years. The older plants, especially in small cities, have usually been equipped with separate units for the railway and the lighting and industrial loads. The development of potential regulators has changed the situation so that there is no reason why power for railway service and for lighting should not come from the same machine. In fact, the use of larger units has the effect of minimizing the bad results due to the sudden fluctuations of load which are incident to railway operation, while not affecting to any extent the control of potential for the lighting circuits.

CHAPTER XVI

SIGNALS FOR ELECTRIC ROADS

Uses of Signals.—The early railroads were operated without signals of any sort. This was possible because the speeds were low and the trains light. When higher speeds and heavier trains became common, it was found necessary to introduce devices to prevent attempts to use the same track for more than one train at a time. This became more and more necessary as traffic increased, and the tracks became more fully occupied. Expressed in modern terms, the primary use for signals is to obtain "Safety First." The need for some form of protection to prevent accidents increases rapidly as the traffic develops, and more particularly as higher speeds are employed.

Another legitimate reason for the employment of signals is to promote, through intelligent use of the track, a greater capacity than is otherwise possible. To accommodate the maximum traffic, trains should follow one another as rapidly as can be done with safety, and speeds should be as high as practical without requiring too great spacing between them to permit stopping in case the track is found to be occupied. The various forms of automatic block signals, when properly applied, will increase by a considerable amount the number of trains which can be run over a given track, and at the same time make the operation decidedly more safe than when other forms of control are employed.

Kinds of Signals.—A number of devices, which are often overlooked in modern operation, constitute the backbone of the signal system on any road. It is well to know which of these are available, and which are used, since they form a valuable adjunct to the better-known types of signals which the public ordinarily considers.

Signals are of two main kinds: audible and visible. The former usually consist of the bell, the whistle and the torpedo. These may be operated by the engineer of the train, or by some other member of the train crew, or in certain cases by members of the operating force not directly connected with the train service.

The use of these devices is invaluable in many critical situations, and must not by any means be overlooked. Visible signals are of two types: movable and fixed. The movable signals are the trainman's lantern or flag, the fusee, and other devices of the same general character. Their use is largely the same as that of the audible signals, and the two are often employed in conjunction.

The fixed signals are those which are placed in permanent locations along the track, where they may be observed by the engineers of passing trains. The simplest of them have one aspect only, and the indication given is to be observed invariably. Such are the whistle post, drawbridge signs, and slow or stop signs. These signals have the effect of warning the engineman of the character of the track ahead, or to remind him of a duty he must invariably perform.

Fixed signals having more than one aspect are often employed; and it is this type which is brought before the public most often in connection with train operation. In this class fall switch targets, train order signals, block signals and interlocking signals.

Methods of Displaying Indications.—In the use of signals of any sort, a great deal depends on the methods employed for imparting their meaning to the train crew. In general, the indication is displayed at a fixed point along the right-of-way, whether for a train-order system, an interlocking signal or a block signal, and regardless of whether the system is manual or automatic in character.

A marked variation in signal indications may be possible when they are to be viewed by day; but for night operation, colored lights are almost invariably employed. The difference between the night signals is due to the methods for changing the color of light displayed. Where electric lamps are used, the most general method for displaying the indication is to have a number of lamps behind colored lenses, the controlling circuits being so arranged that one or more lamps may be lighted to convey different information. With oil lamps, the signal is usually given by a single lamp, the change in color being accomplished by moving a sector with different colored glasses in front of the light.

For daylight indications, the oldest and most widely used device is the semaphore. This consists of a blade, mounted on a suitable support, and in a vertical plane perpendicular to the track. It is rotatable about a fixed point near one end, and the indication is given by its position. There are four possible arrangements of

the semaphore blade, depending on which quadrant is used for the rotation. The maximum rotation used is never more than 90°, one of the positions being horizontal. The American Electric Railway Engineering Association has adopted as standard the following with relation to the use of semaphore signals:[1]

> "Where semaphore signals are used they shall be so arranged as to indicate three positions in the upper left-hand quadrant."

It is rather expensive to install and maintain semaphore signals, so that electric roads have been trying to find other types of indicators which will be satisfactory at a lower cost. Within the last few years, great progress has been made in the use of lamps for daylight signaling. To be satisfactory in this service, the lamp must be equipped with a lens which will properly direct the rays, and be carefully shaded so that it will not be interfered with by direct sunlight. From the excellent results which have been obtained with lamp signals, it seems that they are entirely adequate for day use. On the other hand, there is a large advertising value in any kind of signal system, and the more prominent the indication, the greater the advertisement. Semaphores are without question more readily observed by the traveling public, and their indications are plainer than those of any other form of signal in use; so that from this standpoint they have received more favorable attention in comparison to other forms.

Colored discs have been used to a small extent for day indications, but they possess no advantage over the semaphore and, like it, require colored lights at night. They are now nearly obsolete on all railroads.

Signal Indications.—A signal is to give certain information to the enginemen, and the more certain it is, the better the system. The most usual indications to be given are "stop" and "proceed." In some methods of signaling, a third indication, "proceed with caution," is also used. The standard American Electric Railway Engineering Association's indications are: (*a*) Stop, (*b*) Proceed with caution, (*c*) Proceed.

These may be interpreted in somewhat different ways, depending on the type of signal system used. The "stop" signal usually

[1] *Engineering Manual,* American Electric Railway Engineering Association, Section Ss 2a.

conveys the additional information that there is a train directly ahead, or that some abnormal condition makes it essential that the train should not proceed. It may mean merely that the train crew should report for orders.

The "proceed with caution" indicates that, while it is not safe to go ahead at full speed, it is possible to do so at reduced speed, prepared to stop short of any obstruction. Where the signal

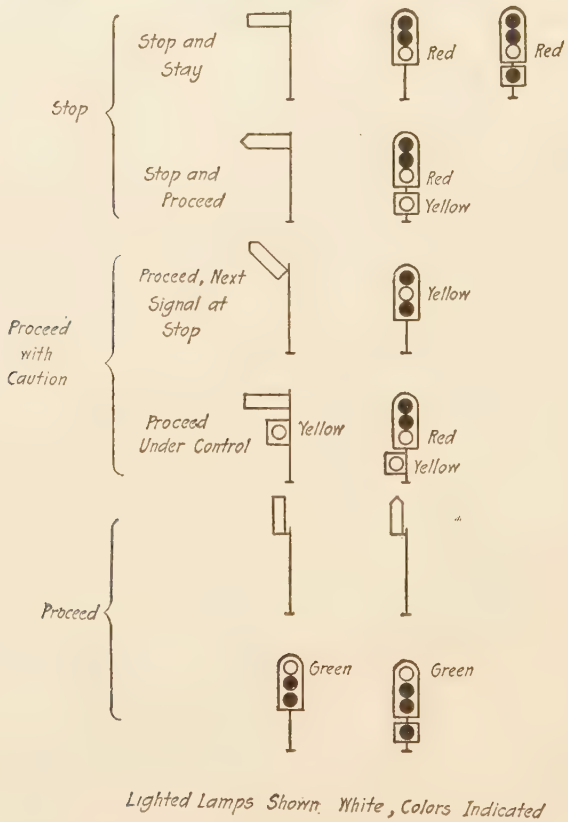

FIG. 183.—Aspects in three-position signaling.

These indications have been adopted as standard by the American Electric Railway Engineering Association.

is used as a preliminary to a stop signal ahead, it may mean to proceed, prepared to stop before reaching the next signal.

The "proceed" indication shows that the track is clear, at least as far as the next signal, and that full speed may safely be maintained.

In America, the "stop" signal is invariably given by a horizontal semaphore, or by a red light. There are two possible locations of the semaphore for this indication, with the blade in a horizontal position, either to the right or to the left of the mast; but the left-hand position is being adopted more at the present time. When semaphore signals are employed for day use, it is customary to have a series of colored lenses mounted on a projection of the blade, so that they will appear in front of a lamp to give the night and the day indications simultaneously.

The "proceed with caution" indication is given by a semaphore inclined at an angle of 45°, or by a yellow light, a combination of lights, or a light and semaphore.

The "proceed" signal is a semaphore in a vertical position in three-position signaling, or 60° from the horizontal in two-position signaling, or a green light. The former use of a white light for "proceed" has been almost entirely abandoned, since there is great danger of confusion with other lights along the road, which might give false indications to the enginemen. The standard aspects in three-position signaling, as adopted by the American Electric Railway Engineering Association, are shown in Fig. 183.

Methods of Train Spacing.—The fundamental principle of train operation, which is almost universally used on railroads, is to have successive trains separated by such an interval that, in the event of an accident to any train, the one following will have sufficient distance to stop before colliding with the first. This has been rigidly adhered to in all systems of train dispatching, and is naturally the only one which will prevent frequent collisions; for conditions may arise at any time which make it necessary for a train to stop at an unexpected place. The exact distance which must be allowed between trains depends largely on the maximum speeds attained, as may be seen by referring to Chapter VII.

Time Interval Operation.—The earliest method of keeping the proper distance between trains was to separate them by a fixed time interval. Provided the train speeds are the same, this will keep them at a constant distance apart, so the proper interval for allowing an emergency stop will always be maintained. But if the first train is delayed, there is no way, after the second one has passed the last station before the forward one is reached, to warn the engineer of the following train that the track is occupied. This deficiency is presumably taken care of by sending back a

flagman from the delayed train, who signals the second one to proceed under control, prepared to find the other train ahead of him. If the first again moves forward at its usual speed, the proper distance will be maintained. The correct time interval can be regained when the next station is reached.

This method is open to serious objections. The first train may not be stopped, but may be forced to run at a lower speed than normal. No flagman will be sent back in such a case, so that there will be no protection for the following train as in the first example. On a curved track, where the engineman of the following train cannot see the rear of the forward one, there is great danger of a collision. Such troubles have been so frequent that the method has fallen entirely into disfavor.

Train Order Dispatching.—A modification of the method consists in placing the entire division under the control of a dispatcher, who is responsible for the proper movement of all trains. By his direction, orders are issued to the crews, specifying meeting points and trains liable to be encountered. Under no circumstances is a crew to proceed without obtaining an order. This procedure gives the dispatcher knowledge of the location of all trains at all times, and should prevent any possibility of accident. The system is usually worked in connection with a published time-table, in which case the regular trains, when running on schedule time, may be relieved from receiving special orders. The train-order method of dispatching is in very wide use in this country, and may be termed the standard method of operation for American trains. The principal objection to it is the danger of a slip occurring in the dispatcher's office, or between him and the crew.

Two methods of transmitting train orders are in general use: the telegraph and the telephone. The former is quite satisfactory, and has been in use for many years. The telephone, while it has only been tried in the last few years, appears to have the same superiority over the telegraph that it has in commercial work. It is more rapid, does not require expert operators, and gives a better chance for direct communication with the train crews, and so informing them of details which may be overlooked with the telegraphic train order.

The Space Interval.—The maintenance of a proper *distance* between trains, rather than a fixed *time*, is evidently the scientific method of protection. Each train carries in front of it a danger zone, determined by the distance required for stopping. The

ideal way would be to have this zone marked in front of the train, arranging that if an obstruction should be encountered, the engineman would be warned, so that he could stop his train within the protected space. This is obviously impossible; but the converse of the method, to provide a danger zone behind, with an arrangement to warn the following train, can be provided in a number of different ways. It is not necessary to make the danger zone absolutely the smallest stopping distance, unless the traffic is so dense as to render it essential. Any distance above this minimum can be employed, and the safety will be even greater. The simplest method of providing the proper spacing is to divide the track into a number of sections, which must be at least as long as the minimum stopping distance. These sections are ordinarily known as "blocks."

Telegraphic Block.—The easiest way to divide the track into blocks is to place signalmen at the proper points, providing them with telegraphic connection to the signalmen on either side. The general method of operation is to allow but one train in a block at one time. Where it enters, the signalman reports to the operator at the other end that he has admitted the train, and the block is then closed to further traffic until it is reported out by the operator at the far end. The block is then clear for a train from either direction, if the road is operated as a single-track line.

The condition of the track is reported to the engineman by word of mouth, by a flag or lantern, or more commonly by a fixed signal, consisting of a semaphore or target by day, and a colored light at night. The signal can be operated by hand or by some mechanical method under control of the signalman.

Controlled Manual System.—It is possible to interlock the signals at the two ends of the block, so that, after the signal has been set to protect a train, it cannot be changed until the train has been reported out at the other end of the block. This is accomplished by having an electric interlock in the operating mechanism, which can be released only by a movement of the controlling switch at the other end of the block. In this form, it is known as the "controlled manual system."

Automatic Block Signals.—Both the plain telegraphic block and the controlled manual depend on the ability of the operators. Although man-failure is fortunately quite rare, there have been enough serious accidents from neglect of duty, misunderstanding, and other similar causes to make it desirable to have some form

of control entirely independent of the human factor. The most logical arrangement is to have the signals operated by the action of the train itself, in which case the reliability depends on the excellence of the mechanical devices used for transmitting the information supplied by the movement of the train.

All the successful forms of automatic block signals use electricity for transmitting the indications. The differences between various systems depend on the means used for the transmission, and for operating the signals. There are two entirely distinct methods of controlling signals electrically: by the use of a separate wire circuit, and by making the rails the conductors of the signal system. In the latter method a wire circuit may be run as an auxiliary.

Wire Circuit Signals.—Signals employing a wire circuit are used to a considerable extent on the shorter interurban roads, and also on city roads. The principle is about the same as that of the two-way switch for operating incandescent lamps. This

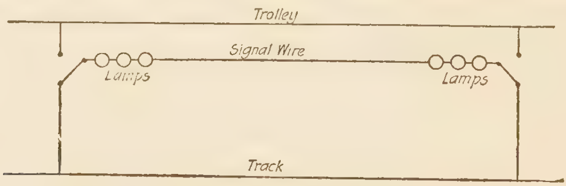

Fig. 184.—Manually operated wire circuit signal.
This contains the essential elements of the widely used types of trolley-contact signals.

arrangement has actually been applied to railway signaling. It may be employed as a manually operated device, as shown in Fig. 184. Here a single wire has in its circuit a number of incandescent lamps, sufficient to burn at about normal brilliancy on trolley pressure. Each end of the signal wire terminates in a single-pole, double-throw switch, which, as shown, may be connected either to the trolley or to the track. In the position given, with both ends of the signal circuit grounded, the lamps will not light, and the same result occurs if both are connected to the trolley. When a train enters the block at either end, throwing the switch to the opposite position will light the lamps at both ends of the block. On leaving, throwing the switch will extinguish the lamps. The only difference will then be that the lamp circuit is connected to the trolley at each end, while originally it was grounded. It is in the proper position that when a train enters the block at either end, the lamps can again be

lighted. This arrangement is suitable for single- or double-track roads, with traffic in one or both directions, and it is used in this form on a number of electric roads, being operated by hand. The greatest objection to the manual signal is that the car must come to a stop, and one of the crew must leave his position on the train to throw the signals.

A development of this simple signal is to have the switch thrown automatically, which may be accomplished by a mechanical trip, but better by a magnet operated from the trolley circuit. When desired, a semaphore can be used in place of the lamps as an indicator.

A modification of the trolley contact signal is made in which it not only indicates whether a block is occupied or not, but also records the number of cars therein, so that the signals are not cleared until all the cars have been counted out. This is accomplished by having the cars pass two trolley contacts, motion in one direction notching up a ratchet, and in the other direction returning it toward its normal position. With one such system as many as fifteen cars can be recorded in this manner.

In signal operation, it is not sufficient to have the "proceed" indication given whenever the block is clear, and the "stop" signal when it is occupied. Conditions may arise when there is no train in the block and yet it is unsafe for one to proceed. Such, for example, are the presence of a broken rail, an open switch, or a train on a siding which is so near the main line that it will foul the track. If any of these be present, the signals should give the "stop" indication. In general, such abnormal conditions are not indicated by signals of the trolley contact type. The use of this type should therefore be limited to places where the liability of danger from such sources is a minimum. Further, there is a prevalent opinion among railway men that the action of the trolley contactors is not entirely satisfactory at high speeds, although the manufacturers claim that their operation is perfect at speeds up to about 60 miles per hr.

Continuous Track Circuit Signals.—To care for protection from conditions such as are mentioned in the above paragraph, an entirely different method of controlling the signals may be used. This is by the use of the track rails as the conductors of the signal system. The American Electric Railway Engineering Association makes the following recommendation:[1]

[1] *Engineering Manual*, American Electric Railway Engineering Association, Section Ss 7a.

"For high-speed interurban service, where automatic signals are controlled by continuous track circuits, that expenditures be concentrated on the form of indication in preference to a more expensive form of signal, and a less reliable form of control."

The original patent covering the use of the track circuit as a control for the signal system was granted to William Robinson in 1872. The fundamental parts of this system are shown in Fig. 185. The track is divided into sections at the ends of the blocks, the rails being electrically separated from each other at these points by insulating joints. At the end of the block where the train enters is placed a relay, similar to the ordinary telegraph relay; while at the opposite end is a closed-circuit battery of the proper size. When there is no train in the block, and the continuity of the track circuit is perfect, a current will

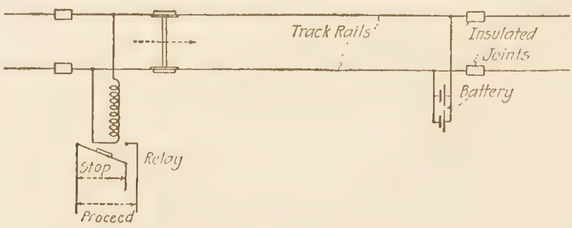

Fig. 185.—Simple track circuit.

In this form, the track circuit signals have been installed on a great many lines of double-track steam railroad.

flow from the battery through the rails, energizing the relay. This operates a local circuit at the signal to give the "proceed" indication. If a train enters the block, the wheels and axles place a short-circuit on the battery, and the relay is de-energized. This causes the auxiliary circuit to open, giving the "stop" indication. It is evident that the same result is obtained if a broken rail exists in the block. By including all switches in the circuit, and connecting the rails of sidings back to a point beyond the fouling limits, protection is obtained from these sources of danger.

The original Robinson device is suitable for the protection of steam roads, on which the traffic is always in one direction. It is the basis of all modern signal systems using the track for the control circuit. There are a number of objections to the system, none of which is particularly serious. The operation depends on

the insulation between the rails being maintained at a fairly high value, since the fundamental idea is to have sufficient current reach the relay to energize it when the block is clear. Although but a few volts are used, the leakage of current during wet weather is considerable. A larger number of cells in series does not aid much, since the leakage is increased somewhat faster than in proportion to the e.m.f. Of the total output of the battery, about 40 per cent. is used to operate the relay, the remainder being used to overcome the resistance of the track circuit and to supply leakage.

Track Circuits for Electric Railways.—The direct-current track circuit, as described, is not suitable for electric railways if the rails are to be used for carrying the propulsion current, since even a small current due to train operation may be enough to give false indications of the signals. In order to make the track circuit applicable for electric railway signaling, it is necessary to make a radical change in some of the details.

The difficulty due to the presence of current in the track can be overcome by using a different kind in the signal circuit, and employing a relay which responds only to that. For instance, on roads having direct current for propulsion, alternating current is suitable for signaling, and a relay of the induction type, which does not respond to direct current, may be employed.

Single Raii System.—Another difficulty in the use of track circuits for electric railway signaling is that the rails must be made continuous if they are to carry the main current. If conditions are such that the conductivity of one rail is sufficient for the purpose, or if auxiliary conductors can be installed, one of the track rails can be used for carrying the line current, while the other is cut into insulated sections to form the signal blocks. The arrangement of circuits is shown in Fig. 186. It may be seen that a lowering transformer replaces the battery of the direct-current signal circuit, a supply of alternating current being furnished by the signal mains. To limit the current which can flow when a large difference of potential exists in the return conductor rail between the ends of the block, a certain amount of non-inductive resistance is inserted in the circuit. To prevent any magnetizing action from what direct current does pass through the signal apparatus, the transformer is made with an air-gap, and a reactance coil, also with an air-gap, is shunted across the terminals of the relay. The action of the latter is like that in the direct-current signal system, but the type is

different, being similar to a single-phase induction motor. The action of the signal mechanism may be the same as with direct-current track circuits; but, since a supply of alternating current is present for the track circuit, it is simpler to use it throughout, induction motors being employed for operating semaphores. When lamps are used for the indications, they can be supplied from the signal mains through lowering transformers.

It is evident that the same protection is given with this system as with the direct-current track circuit. A broken rail or a fouled switch can be made to indicate equally well. The principal objection is that only one of the track rails is available for the return circuit; and in some cases additional feeders must be installed. For an elevated or a subway line, this defect is not

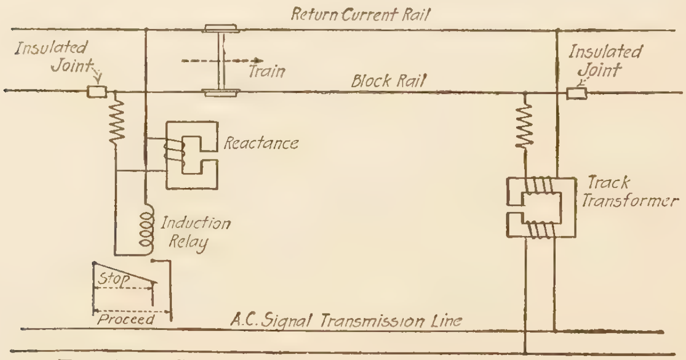

FIG. 186.—Single-rail alternating-current signal circuit.

This type of track-circuit signal is suitable for electric roads using direct current, or for steam roads where there is danger of interference from stray current in the rails.

serious, since the metal structure can be used to supplement the track; but for an interurban road the cost of additional copper may be prohibitive.

For steam roads, the alternating-current system is finding more favor at present than the direct, since stray direct currents due to leakage from electric lines are liable to derange the signal circuits. This may be obviated by the use of alternating current for operating the signals, as described above. In this case both rails may be divided into insulated sections.

Double Rail Alternating-Current System.—If the propulsion current can be prevented from interfering with the action of the signal mechanism, it will do no harm in the rails; but to keep the blocks separate is a more difficult matter. The method already

described sacrifices the conductivity of one rail. Another way is to use a form of bond which will pass direct current, but will not allow alternating current to flow through. Such a bond may be made by the use of balanced inductances. The arrangement is shown in Fig. 187. The insulated joints are retained, as with the direct-current track circuit, but the two rails in each block are connected by inductance coils, which are joined together at their middle points. The obstruction to the flow of direct current is small, since the resistance of the bonds is low; but there is no tendency for the alternating current to pass such a bond, for the two sides of the track in the adjacent block are balanced.

If the direct current is evenly divided between the two rails, the unbalancing in the inductive bonds is negligible; but when the

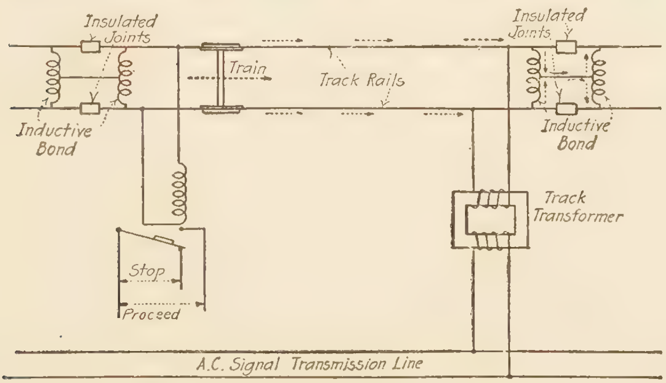

FIG. 187.—Double-rail alternating-current signal circuit. Suitable for use with direct or alternating propulsion current.

difference between the currents carried by the rails is large, it is necessary to introduce an air-gap into the core of the bond to lower the inductance. The more perfect balancing of the potential drop between the two rails renders the use of an air-gap in the magnetic circuit of the lowering transformer unnecessary, and makes it possible to dispense with the regulating resistance and with the reactance shunting the relay, as used in the single-rail system. A similar induction relay, which responds only to alternating current, is employed. The other parts of the apparatus can be the same as for any form of track circuit signals.

As described, the alternating-current track circuit signal system is suitable for use in connection with roads employing direct current for propulsion. It is equally applicable to single-

phase or three-phase lines, provided the frequency of the signal circuit is so chosen that the inductive bonds will pass the propulsion current, while holding back that for operating the signals. This can be accomplished by using a higher frequency for the signal system, with an amount of inductance in the bonds which has a small effect at the line frequency. For 25-cycle roads, 60-cycle signaling current is entirely satisfactory in actual service.

Methods of Operating Semaphores.—When semaphores are used for the daylight indication, it is necessary to have a more complicated mechanism for operating them than is employed with lights alone. The semaphore usually consists of a wooden blade, pivoted at one end, and counterweighted so that the unbalanced mass is small. When arranged for use in an upper quadrant, the blade is slightly heavier than the counterweight, so that it will fall to the "stop" indication if the mechanism fails to hold it at "proceed" for any reason, whether in the normal operation of the system, or through failure of the signal apparatus. On the other hand, semaphores for indication in the lower quadrant have the counterweight the heavier, producing the same result. The great advantage of the upper quadrant signal is that if the blade is weighted with a coating of ice sufficient to prevent operation, the blade will fall to the "stop" indication rather than to "proceed." This is a safety precaution which has great value, and is extending the use of upper quadrant signals.

The semaphore is ordinarily moved to the "proceed" indication by a small electric motor, driven by batteries in direct-current signaling, and by a transformer from the signal mains in the alternating-current systems. After the proper movement is made, the motor is automatically disconnected, and the blade held in position by an electromagnet. In all types of signals the apparatus is so arranged that a failure of the operating current, or of any part of the mechanism, will cause the signal to give the "stop" indication.

Permissive Operation.—The signals discussed so far are of the absolute type. That is, the indication is either "stop" or "proceed." There may be many instances where it is not necessary for the train to stop and remain at the signal, but where movement with extreme caution will be sufficient to guard against accident. In any of the absolute systems, such as those described, permission may be given by the operating rules to disregard the signal indication under certain conditions. When a train is halted by

a signal set against it, the indication may be due to an open switch, a broken rail, or a train on a siding within the fouling limits. To save time, the engineman is allowed, after having waited a reasonable length of time, to enter and proceed slowly, being prepared to stop short of any obstruction. If a train is in the block, it is still protected by the slow speed of the second train, and if one of the accidental conditions is encountered, or the signal mechanism is out of order, it can be reported by the train crew. When operated in this manner the signal system becomes permissive to a limited extent.

Preliminary Signals.—It is not always possible to locate the signals at such points that they may be seen for great distances

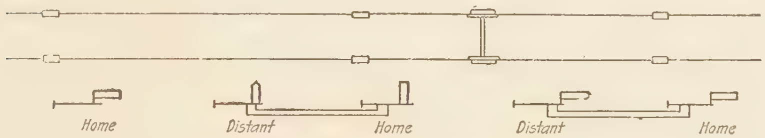

Fig. 188.—Use of distant signals.

The home signal is repeated at a point far enough ahead that the engineer can get his train under control, prepared to stop when necessary before reaching the home signal.

along the track. In order to be effective, the distance which a signal can be observed by the engineman must be sufficient to permit stopping the train before passing it. If there are obstructions along the track, it may be necessary to repeat the indication at some point in advance of the signal. The arrangement is shown in Fig. 188. The indication of the home signal is merely

Fig. 188.—Combined home and distant signals.

The operation is the same as shown in Fig. 188; this arrangement is used when the blocks are short enough to warrant it.

repeated, but it is read differently. The distant signal in the forward block shown may be read: "Proceed at full speed; expect to find the next home signal in 'proceed' position." The distant signal in the rear block indicates: "Proceed, prepared to stop at the next home signal." If the distant signal is placed at least as far as the stopping distance ahead of the home signal, ample warning is given the engineman to get his train under control. If, in the meanwhile, the train occupying the block

ahead has passed out of it, the engineman of the second train can resume full speed as soon as he sees the "proceed" indication of the home signal.

When the blocks are necessarily short, it becomes more economical to mount the two semaphores on a single mast, or to combine them in a single three-position signal. In the latter case, the arrangement is shown in Fig. 189. The indications are as before; but the same semaphore may give both the distant indication for the block ahead, and the home indication for its own.

Signals for Operation in Two Directions.—The signals so far considered are all designed for normal operation in one direction only, or, in other words, for double-track roads. To provide an absolute block system for a single track does not present much

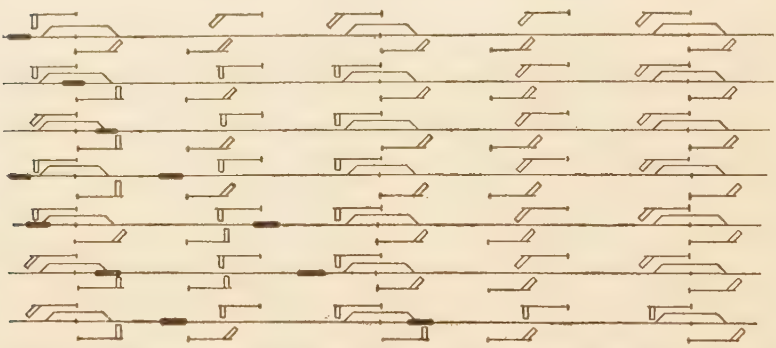

Fig. 190.—Single-track signaling. Positions of semaphores for following cars.

additional difficulty, requiring principally that arrangement be made to show the proper indication at each end of the block, instead of at one end only. A simple method of accomplishing this is to place the battery or transformer supplying the track circuit at the center of the block with relays at each end. The conductance of the train is so much greater than that of the relay, that if the size of battery or transformer is properly chosen, the presence of a train will prevent enough current reaching the relay to operate it, so that the signals at both ends of the block will give the "stop" indication. While this arrangement will give protection, and can be used with or without preliminary signals, it limits the capacity of the block to one train at a time. It is possible to operate several trains in the same direction in one block, provided the signals will give proper protection; but, with

the ordinary types controlled by the track circuit, it is not easy to do this.

A recent type of track circuit signal is arranged to give control so that two cars may be in a block between sidings, if moving in the same direction, while they must be spaced a distance apart at least one-half of the total block length. The arrangement of signals in this system is given in Fig. 190, the progression of two following cars through the blocks being shown, while in Fig. 191 the movement of two opposing trains is seen. Details of the equipment and methods of operation are given in recent issues of the *Electric Railway Journal.*[1]

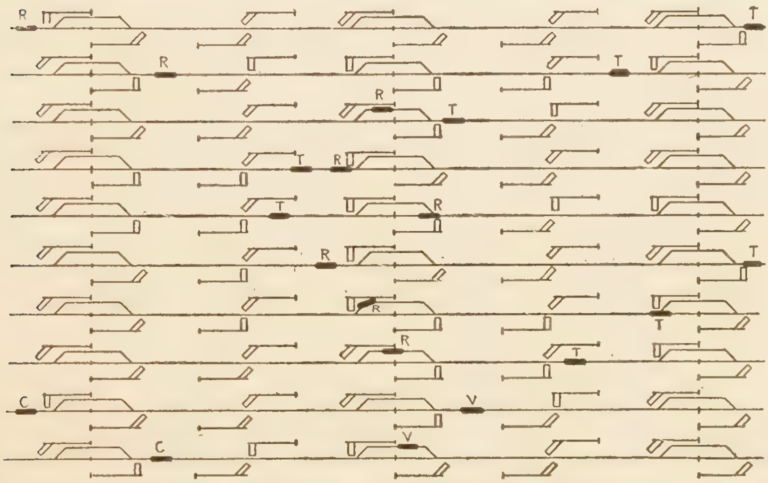

Fig. 191.—Single-track signaling. Positions of semaphares for opposing cars.

Cab Signals.—In bad weather, there is always difficulty in observing the indications given by roadside signals. This condition calls for extreme care on the part of the engineman to prevent running past them. In extremely bad weather, it may be necessary to reduce the running speed; and some serious accidents have occurred through inability of the engineman to observe the signals.

[1] A New System for Track Circuit Signaling Without Preliminaries; *Electric Railway Journal,* Vol. XLIII, p. 199, January 24, 1914.

A New Method of Traffic Acceleration on the Scranton & Binghamton; *Electric Railway Journal,* Vol. XLIV, p. 602, October 3, 1914.

If the signal indications can be given in the locomotive cab, instead of at a fixed point along the track, it is evident that running conditions will be considerably improved, especially in bad weather. This has been accomplished in at least one system. The operation is quite similar to that of a trolley contact signal, the connection being made by a ramp alongside the track, which presses against a shoe on the car or locomotive. By this means an indication is given which is the same as the corresponding one at the fixed signal. It may be operated by a track circuit, the action of the ramp being controlled thereby; or the ramp may be used in connection with a trolley contact.

Cab signals possess the advantage of presenting the indication to the engineman at all times, so that there is no valid excuse for running past a "stop" signal. This feature is one which is worthy of considerable attention from railway operators.

The Automatic Stop.—For many years it has been desired to have a suitable means of absolutely preventing disregard of the signal indications. On all railroads some form of surprise test is made at irregular intervals to determine whether the indications are being obeyed. This arrangement, while getting better service, is a crude way of checking the effectiveness of the signal system. A method which absolutely prevents improper operation is the best, and next to that is the determination of every infringement of the rules.

Methods of stopping trains which run past danger signals have usually been confined to devices for applying the emergency brakes. The earliest arrangement consisted of a glass tube connected to the air-brake system, and mounted on the roof of the car or locomotive in such a position that it would strike an arm projecting from the semaphore blade, and moved therewith. Passing of a "stop" signal breaks the glass, and applies the emergency brake. If a tube has been broken, it must be replaced with a good one in order that the train may proceed. A duplicate tube is furnished each train crew; but the fact that one has been broken is an indication in itself that the signal has been disobeyed. A modification of the system, in use in the subways and tunnels around New York City, is identical in principle, but employs a mechanical trip projecting from the roadbed, which opens a valve on the train.

It is usually desirable to make the automatic stop permissive, in the same way that the fixed signal is permissive. To do this,

an arrangement must be made so that the train crew can unlock the stop, and proceed by it, when allowed under the rules. This may readily be done; and it prevents loss of time in case a false indication is given, or if any of the abnormal conditions which may exist are present.

Automatic Train Control.—It is but a short step from the automatic stop to the entire automatic control of train operation. The former, as described, will stop a train only when it has already passed a "stop" signal. It is possible that the train which causes the indication is directly ahead of the signal, in which case there would be no additional protection due to the automatic stop. To make the latter effective in such emergencies, the stop should be located at the distant or preliminary signal. This, again, has the disadvantage that if the block should be cleared before the train reaches the home signal, the operation of the stop will cause an unwarranted delay. The ideal control is to have a form of trip operated in such a manner that it will cause the train to reduce speed on passing a distant signal giving the "proceed with caution" indication, but not forcing a stop unless the train overruns a home signal displaying "stop." By this method the speed of the train will be under control from the time the distant signal is passed, whether the engineman obeys the indication or not.

Up to the present time, no system has been developed which has proved entirely satisfactory. In a prize competition held by the New Haven road a few years ago, no less than 1800 entries were made. From the amount of interest in the subject, as evidenced by this large number of competitors, it would seem that a satisfactory solution of the problem may be made within the next few years.

Interlocking.—At points where several lines of railroad track diverge, or where roads intersect, there is an exceptionally dangerous situation. In many cities, where the lines cross steam railroad tracks at grade, it is customary to have a flagman, or to have one of the train crew flag the car across the tracks. This slows down the schedule speed considerably, and is not absolutely safe, especially where there are but few steam trains. Interurban and steam railroads usually guard their tracks against collisions by the use of interlocking plants at the points of intersection.

The interlocking plant consists of a set of "stop" signals, so interconnected that it is impossible to give the "proceed" indication on conflicting routes. Combined with this is a set of

derailing switches to prevent the progress of trains which might disregard the "stop" signals. Detector bars are usually employed to prevent a rearrangement of the signals while a train is in the act of passing the intersection. By these precautions, a collision is impossible, even when the indications are disregarded, unless the apparatus is out of order.

The operation of the interlocking apparatus may be accomplished by several methods. The simplest of these is the plain mechanical interlocking machine, which has been in service on many roads for years. The power for operation is supplied by a signalman, who is located in a tower where he can see the entire set of tracks under his supervision. The levers of the mechanical machine are somewhat heavy, and require a considerable amount of force to operate. The movement is necessarily slow.

Improvements on the mechanical interlocking machine have been mainly in the substitution of some easily controlled power for manual. The most successful forms of power interlocking machines are the electric and the electropneumatic. The methods of operation of the two are almost identical, the main difference being that in one compressed air is employed for throwing the switches and signals, while in the other electric motors and electromagnets are used. In both the movement is controlled electrically.

The principal advantages of power interlocking of the two kinds mentioned are that the time of operation is reduced by about one-half, that the space required in the interlocking tower is but about one-fourth, that the number of operators is materially reduced, and the space needed for connections between the tower and the signals and switches is much less. These advantages are sufficient to justify the use of power apparatus in any but the smallest plants.

CHAPTER XVII

SYSTEMS FOR ELECTRIC RAILWAY OPERATION

As was stated in the first chapter, there are several possible combinations of electric circuits and motors for the operation of railway trains. The various elements have been considered separately, and it now remains to bring together the details which make up the complete systems. Of the possible combinations, the direct-current, the three-phase, and the single-phase circuits have been used for supplying the propulsion current to the cars. These will be taken up in order, so that the merits of each can be discussed.

600–Volt Direct-current System.—This is the oldest type of electric railway distribution at present in use. As has been mentioned in previous chapters, it is a gradual development from the low-pressure circuits with which the early roads were equipped and represents about the safe limit of potential for continuous operation of motors without interpoles.

The motors used are almost invariably of the series type. Due to the long period of development, they are well standardized, and the minor defects have been eliminated to a large extent. No more reliable and satisfactory motors are known for use on railway circuits. The direct-current series motor, when adapted for railway operation, is as light as any, and, since the parts are comparatively simple, it is one of the cheapest motors available. Furthermore, the standard machines are quite efficient, although no attempts have been made to attain the very highest efficiency. Ruggedness and freedom from breakdowns have been considered more desirable than refinements.

The series motor has a great advantage over other types, in that it automatically protects itself against overloads. Since the same current flows through both armature and field, a sudden load thrown on the machine cannot cause a great increase in armature current without a corresponding gain in field strength, so that the motor slows down when an overload is encountered, and does not draw such a great rush of current as do other types under similar conditions. With the addition of interpoles, the

troubles due to overload and to variation of the supply potential are minimized to a point where they have practically no effect on the satisfactory operation of the machines.

If a need arises, as for instance to get characteristics suitable for regeneration, the shunt motor can be used; and if desired, the compound motor is also available for operation on the direct-current circuit. In this way, speed characteristics of any form whatever may be obtained with this system, although up to the present time the series motor has fulfilled all requirements.

The control of direct-current motors, while quite satisfactory, is scarcely up to the standard set by the motors themselves. It has been shown that there is a considerable loss of energy in the resistors while starting, which is an inherent defect, and which cannot be remedied without the use of very special methods which are so complicated as to have but limited application. With the ordinary forms of series-parallel control, there are but two, or at best three, efficient operating speeds. By the use of field control, as many more speeds may be added at the cost of a slight complication of the circuits. Field control also reduces the energy consumption when direct-current motors are used for mixed service, such as combined city and interurban lines.

The contact line is extremely simple. Either the third rail or the overhead trolley may be used, or, if special conditions demand it, the underground conduit or perhaps surface contact can be satisfactorily employed. While these special forms of contact conductor might be used with other distribution circuits, they are not suited to higher potentials, which form the basis of all the other systems.

The low-tension distribution, which is responsible for the extreme simplicity of the 600-volt system, is in itself the great source of inefficiency. The loss in the distributing circuit is necessarily large,.whether in energy when a small expenditure for copper is made, or in overhead cost when a larger conductor is used. This is the great drawback to the universal application of the system. It is so serious that, even for city roads of comparatively great congestion and short length, it is necessary to generate alternating current for the economy it offers in high-tension transmission, and to add the somewhat complicated and inefficient link of lowering transformers and rotating converting equipment.

An incidental disadvantage, which is exceedingly difficult to completely combat, is the trouble caused other corporations who

have metal structures buried in the soil, by electrolysis. The low-potential distribution is a great contributing factor in this, since it calls for large currents to be transmitted through the rails, unless an insulated return circuit is provided. While it is conceded that, with great care, electrolysis can be prevented, it is difficult to maintain the grounded return circuit in such excellent condition that trouble is not liable to arise almost without warning.

In spite of the disadvantages, the excellence of the 600-volt system is such that it has been universally used for city service, and for this class of operations it is unquestionably without an equal. It is not probable that any other method of distribution will be advanced which will drive the 600-volt system out of this field. For interurban service it has been in the past nearly always adopted; but the use of higher potentials will probably supersede the low-tension system more and more where the length of distribution is great.

High-Tension Direct-Current Systems.—The use of direct current at higher potentials has followed the need for a reduction of the loss in the distributing circuit, especially for long lines. Motors of the interpole type must be employed, and the use of higher potentials has been entirely dependent on the development of this kind of machine. They possess the same excellent characteristics as the 600-volt motors; and, in fact, where a 1200-volt contact line is used, there is no difference in their construction save the need for more insulation. On account of this, the output of a given motor must be somewhat less when wound for use on the higher pressure, so that the motors are not so light, so cheap, or so efficient when so arranged. The difference for 1200-volt operation is comparatively small, so that no great effect due to this cause is apparent. When the motors are wound directly for the 1200-volt circuit, the difference is greater; but since this change is usually made to permit the use of a contact line at 2400 volts, it is entirely justified.

The control for the higher potentials is more expensive than for 600-volt equipment. The arcs are more difficult to break, so that greater distances between the switch blades, better magnetic blowouts, and longer arc chutes are required. It is sometimes even necessary to place two breaks in series to prevent damage from the arcs. On account of the smaller current, when the energy to be dissipated remains the same, the resistors used must

be of smaller cross-section and greater length. This leads to a more expensive and less rugged design.

The great advantage in the high-tension system lies in the saving in cost of the contact line, either of the conductor or of the energy lost in it. This is the cause of the adoption of the higher potentials. In the lines so far constructed, it has not been found practical to generate direct current at the contact line potential; but alternating-current generation, with high-tension transmission and conversion to direct current through rotating machinery, has been adhered to. The highest potential at present in use on the contact line is 2400 volts, while one installation for operation at 3000 volts is now being constructed. These values are still far less than those which have been considered suitable for transmission; and even if decidedly higher contact line pressures are used, it does not seem likely that this link in the electric system can be eliminated.

One possibility, which has been increasing in importance in the past few years, is the use of mercury vapor converters for producing a unidirectional current for the contact line and motor operation. While it is yet too early to make any definite statements, it may improve the efficiency of conversion by a large amount.

A minor disadvantage in all the high-tension direct-current systems is the difficulty of obtaining suitable current for the operation of auxiliaries, such as air compressors, lights, heaters and minor apparatus. In some cases the pressure has been cut down directly by the use of resistance, while in others special dynamotors and motor–generators have been used to transform to a lower potential. None of the solutions thus far advanced seems entirely satisfactory.

In any of the direct-current systems, the return of energy to the electric circuit is difficult, unless motors with a shunt characteristic are employed. Since one of the advantages which has always been claimed for direct current is the use of motors of the series type, it would mean an entire revolution in operating methods to make the complete change to shunt motors. By the use of separate windings or by special connections of the series fields, it may be possible to provide this feature in direct-current equipments. It must be admitted, however, that the use of coasting will reduce by a considerable amount the advantage to be gained by regeneration.

Three-Phase System.—The use of alternating current was introduced in Europe about 15 years ago, the distribution being by the three-phase system. At that time the only motor which could be used for traction on such a circuit was the polyphase induction motor. Although other types of polyphase machines, employing commutators, have been developed since then, none of them has characteristics which would be suitable for railway service, or would give better results than the induction type. Three-phase distribution may be said to call for the use of the latter as a necessity.

The induction motor is one of the most rugged machines built. In the squirrel-cage type, the secondary is a compact structure, not connected in any way to the external circuit, so that no commutator or collector is required. The secondary winding is exceedingly simple, consisting of heavy copper bars short-circuited to resistance rings at the ends of the core. The primary winding is not complicated, being comparable to that of a direct-current armature without the commutator. When it is necessary to employ a wound secondary, as is usually the case, a regular phase winding similar to that on the primary is used, and the terminals are connected to a short-circuiting resistance through collector rings. In this form the motor is slightly more complicated than the squirrel-cage machine, but the difference is small, and the simplicity of the design is still much greater than that of any motor using a commutator.

The induction motor is probably the lightest of any built for railway service, and is correspondingly cheap. The efficiency is quite high, and the power factor may be made satisfactory for commercial purposes. The difference in performance between the induction motor and the direct-current series motor is slight; but if there is any advantage, it is on the side of the alternating-current machine.

The disadvantage of the induction motor lies in the fact that it is a constant-speed machine. Although the advocates of the three-phase system claim that constant speeds are preferable, railway operators in the United States are not convinced that it would be desirable to change from the variable speed which has characterized the operation by steam locomotives for nearly a century. On the other hand, it may be argued that there are but a few speeds available with direct-current series motors, although these few, unlike those of the induction motor, are not constant

over a wide range of load. It is difficult to make a fair decision between the two methods, for the data at hand with regard to constant-speed operation of large railroad systems is entirely inadequate for a comparison.

The method of control used for induction motors is somewhat similar to that for direct-current motors, in that the speed is lowered at starting by the use of resistance in the motor circuits. If concatenation of motors, or other means to give a reduced running speed, be used, the losses in the control resistors are not much greater than when direct-current motors are operated with series-parallel control. In many ways there is but little choice between the two. The alternating-current control has one marked advantage, in that the potential to be handled is low, and is in a local circuit, where disarrangement of the resistor connections can do but little damage; while the resistors in the direct-current control are inserted in the main circuit between the contact line and the motors. With induction motors the main circuit need not be opened at all when power is being drawn from the line, so that the danger from arcing at the controller contacts is reduced to a minimum.

The great disadvantage of the three-phase system is the complicated contact line. Using the track rails as one conductor, two additional lines are necessary, so that two parallel trolley wires, each carrying the full potential, must be supported above the track. The greatest difficulty is found in maintaining the insulation between these conductors. This is especially true where there are many turnouts, crossovers, and other special work, since the wires of opposite potential must be insulated from each other. These difficulties have limited the pressure in most cases to about 3300 volts, so that the primary purpose of the three-phase distribution, to allow a high working potential, is in part defeated. Aside from this, the distribution is quite flexible, since the e.m.f. can be changed by stationary transformers placed along the track, and, if the motors are wound for lower pressures than the trolley, reducing transformers can be placed on the locomotives and cars.

The economy of the distribution system is quite high, for in spite of the fairly low potential, there is a considerable saving in loss due to the inherent property of the three-phase circuit, that three conductors give the same loss as four of the same cross-section in the two-phase system, or two of double section in the

single-phase or direct-current systems, for the same effective pressure.

With the three-phase system, using induction motors, regeneration of energy on down grades can be obtained automatically without any modification of the control circuits. All that is required is to leave the motors connected to the line. This is especially useful when heavy freight trains must be handled on long down grades, in which case the control of the train without the use of brakes is safer, and gives considerable saving in brake-shoe wear.

The Single-Phase Alternating-Current System.—This is much more flexible than the three-phase system in the range of equipment which can be applied. Most of the installations up to the present time have used machines of the commutator types, with characteristics nearly the same as those of the direct-current series motor. While these are quite satisfactory from an operating standpoint, they are considerably more complicated, are from 10 to 20 per cent. heavier for the same output, and correspondingly more expensive than direct-current series motors of the same rating. This disadvantage is partially overcome by operating the single-phase machines at higher speeds, although this has in itself some objections. Single-phase commutator motors have full-load efficiencies from one to two per cent. lower at full load than direct-current motors.

By the use of a "phase-splitter," three-phase induction motors may be operated on the single-phase distribution circuit, thus giving a performance identical with that of the three-phase system. In some cases the use of this combination may be justified; and it is actually being applied in one instance in America.

If the mercury vapor rectifier fulfills the present expectations, it will make the single-phase circuit available for use in connection with a suitable type of direct-current motor, giving any required range of characteristics.

The control of single-phase series motors, or of direct-current motors through a rectifier, is quite simple, and is much more efficient than the series-parallel control used with direct-current circuits. If three-phase motors are employed, the control must be effected with resistance alone, or in combination with concatenation or pole-changing connections, in which case the efficiency is about the same as for the direct-current system.

The single-phase contact line is simple, and in this respect is

on a par with direct current. The principal argument in favor of the single-phase system is in the high tension which can be used effectively on the contact line; and it is in this respect that it is ahead of all the other methods. With the aid of lowering transformers on the cars or locomotives, the motors can be wound for any suitable pressure, irrespective of the distribution potential. There has been no serious difficulty in maintaining good insulation of the contact line at pressures as high as 20,000 volts. This high potential reduces the current to a point where the conductor section can be very small; in fact, the size of the trolley wire for mechanical strength is in practically every case great enough that no supplementary feeders are necessary, even for heavy traffic.

The distribution circuit as a whole is the simplest in character of that for any system, and the converting equipment consists only of single-phase transformers of the proper rating, spaced along the track. The high distribution potential makes possible the use of long distances between substations, so that the load-factor is improved over that obtained with any system operating at a lower pressure. In addition, the use of a control consisting of taps from the secondary of the car transformer makes the actual value of the potential drop of very little importance, and high accelerating current or high speed may be maintained under practically all conditions.

Rotating machinery is required in the distributing circuit only when it is necessary to change the frequency; and, as satisfactory motors can be designed for 25 cycles, there is little difficulty in using standard apparatus, without frequency changers. If it is found desirable to generally adopt motors designed for operation on a frequency of 15 cycles, either a separate generating and distributing system must be provided, or else rotating frequency changers must be used. But the recent developments, mentioned in the preceding paragraphs, in the use of different types of motors on the single-phase contact line may make such an arrangement unnecessary. With the use of the rectifier, it would even be possible to operate the system at the commercial frequency of 60 cycles.

So far as can be determined, there is no danger of electrolysis with alternating current, although this advantage is slight, since the single-phase system is best suited to cross-country work, where the danger to other metallic structures in the surrounding earth is a minimum.

If induction motors are used, regeneration of electric energy is automatic; but while it is easily possible to recover energy with single-phase commutator motors, it is questionable whether the complication in the control would not offset the advantages to be gained.

Field of the Systems.—Up to the present time, the use for city service of the 600-volt, direct-current system is universal in America, and practically so all over the world. While this may be due largely to its early application in all importantinstallations, there is no conclusive argument to be made against it. The series motor has the characteristics required for rapid acceleration; and, although the direct-current control is somewhat inefficient, the loss due to the extra weight of apparatus for single-phase operation leaves a wide margin in favor of the former. The use of the low-tension distributing circuit is to some extent a disadvantage, but the distances through which the direct current must be transmitted are relatively quite short, so that the total loss is not excessive. One of the worst features incident to direct current in city service is the necessity for locating substations at central points where the cost of real estate is high. Another disadvantage is the danger of damage from electrolysis. This latter trouble can be overcome to a great extent by the proper maintenance of the return circuit, and it is seldom necessary to resort to the heroic remedy of using two trolley wires.

For suburban and interurban service, where a portion of the run must be made over city streets, a combination system which will allow the same motors to be used for all parts of the road is desirable. The earlier lines of this class are all equipped with the 600-volt system, as it was the only one available at the time they were installed. A few roads, built about ten years ago, were equipped with single-phase series motors, with a duplicate control so arranged that they could run either on alternating or direct current. In practically every case such operation has been to a large degree unsuccessful, mainly on account of the great complication and excessive weight of the equipment. For this class of service the use of 1200 volts direct current has been a more satisfactory solution of the power supply problem, since the added complication to adapt the motors and control for both circuits is comparatively small. A large number of roads, formerly using 600 volts, have rearranged their distribution circuits to admit of 1200-volt operation, with satisfactory results.

For heavy service, any of the systems are available, and all of them are used. There is no general agreement as to which is the best suited for all-around railroad work; but it is quite evident that for long-distance lines a high-tension distribution circuit is a prime necessity. This of course rules out the 600-volt system from consideration for such roads, although where it has been installed for terminal service, it has in all cases given good satisfaction. In America, the choice seems to lie between the single-phase and high-tension direct current. Developments are taking place so rapidly at the present time that it is impossible to predict that one or the other system will prove greatly superior. There is no immediate prospect of the use of direct potentials comparable with those for single-phase circuits; but the lower distribution losses incident to direct current put it more nearly on a par with its competitor than it otherwise would be Three-phase distribution has not been a serious factor in this country, although it has been very successful abroad in several important installations. In view of recent developments, it is doubtful whether the straight three-phase system with induction motors will meet the needs of American railroads.

Single-phase operation has the greatest possibilities for heavy service. The ability to use any known type of propulsion motor, with the converting equipment on the locomotive, makes it as near a universal system as can be obtained. Even if some roads should adopt other methods of distribution, it is still possible to design single-phase locomotives so that they can be run efficiently on such circuits. With induction motors, the same locomotive could be operated on three-phase circuits with a comparatively slight complication of the control; and the same is true of direct-current motors if used on the single-phase circuit through some form of converter. Recent developments make it seem doubtful whether the alternating-current commutator motor will survive, at least in its present form; but the use of this machine is only an incident to the successful development of the single-phase system.

CHAPTER XVIII

ENGINEERING PRELIMINARIES

Electric Railway Location.—The proper location of an electric railway is a problem involving a considerable number of variables, all of which must be given consideration if the best possible result is to be obtained. The quantities entering are so numerous and so diverse that it is almost impossible to determine absolutely in all cases the best location, equipment and schedule. The last quantity is one which can be modified at will, within the limits of the rolling stock and the electric system; but the first two, when once chosen, are quite difficult to modify without incurring a large additional cost. It is, therefore, exceedingly important that the preliminary engineering be very carefully done, since the final success of a road may be seriously jeopardized if mistakes are made at this point.

City Roads.—The requirements of nearly all cities of large or moderate size for purely urban transportation have been largely met at the present time, so that a study of the requirements for such lines is almost entirely academic. The method of determining the proper equipment is of some value, as it gives a means of checking existing installations as to their adequacy. In some cases, where the present facilities are insufficient, such a study may lead to the extension of the lines to meet the needs of the inhabitants.

The length of track which a city can support is, to a large extent, a function of the population. The relation of population to length of track per thousand inhabitants for a number of American cities is shown in Fig. 192. It will be seen that the proportional length of track which a city can support decreases as the density of population increases up to a certain point, after which it becomes sensibly constant. This would be expected, since the smaller cities, in order to give any kind of service, must provide relatively large amounts of track, even though the number of passengers carried is comparatively small. As the size of cities increases, the use which is made of the existing track is

greater, so that the additional amount of line which has to be installed per inhabitant becomes decidedly less in the larger urban centers. A saturation point is finally reached, beyond which the increase in necessary track is practically in proportion to the population. The place where this condition occurs depends largely on the compactness of the city and the number of independent centers which exist within the community. The more concentrated the population, the less is the ultimate limit for the amount of track per inhabitant.

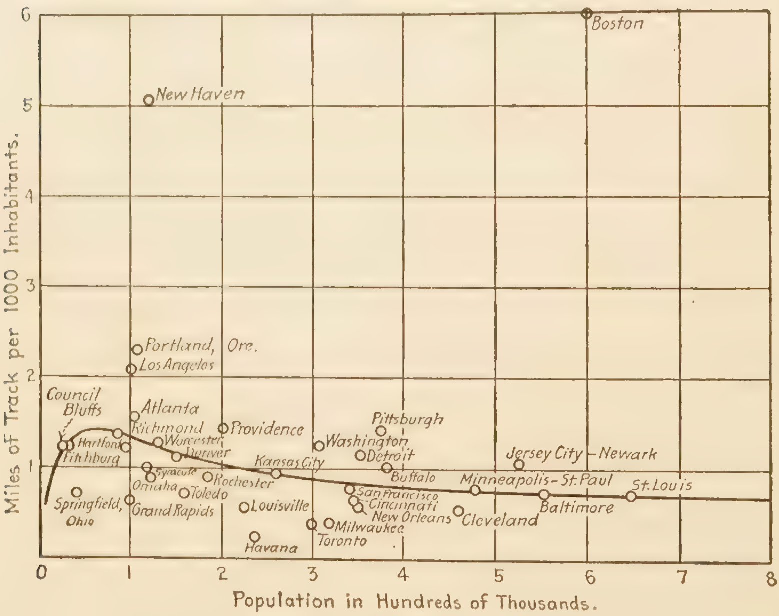

FIG. 192.—Relation of urban track to population.

In some cities the amount of track which can be used is much greater than the average. Boston, for instance, has a much greater length per inhabitant than any other American city of similar size. This difference is more apparent than real, for a large population in the immediate vicinity of the metropolitan district is served by the same system, so that additional facilities for the adjacent cities are not required. The extra demand for transportation from the surrounding suburbs will increase the use of the city railway tracks, so that the earnings may be exceedingly high when a line is located in such a center. Another cause for

extensive use of the road is when the physical location of the city is such that it is impossible or difficult for the inhabitants to walk to and from their homes. An example of such a city is New York, where the business district is of such a character that very few persons can live within easy walking distance of any point in it. For this reason, an adequate transportation system must be provided to permit the further development of the city. In fact, in New York the growth of the city railroads is decidedly behind the increase in population, so that the existing facilities are strained to the utmost. Similar conditions exist in many other places, but the results cannot be so clearly seen as in the former city.

Future Requirements. In addition to determining the present need for railway facilities, it is necessary to make some provision for future growth, if the requirements of the city are to be served for any length of time. In certain cases it is possible to make such provision merely by the extension of the existing tracks farther into the suburbs, as these develop; while in others the growth of the urban section may make a complete rearrangement of the entire road necessary. Careful design of this part of the system may add considerably to the growth which can be taken care of without extending the existing tracks. In a number of the smaller cities it has been customary to route all cars past a central point, such as an important street intersection or a civic center. Although this practice makes the transfer of passengers simple while the traffic is light, it is likely to cause serious congestion when the city has developed to a larger size. In some places where this arrangement has been used, considerable objection by the public has developed to the re-routing of cars on different thoroughfares. This condition can only be overcome by careful publicity work on the part of the railroad company.

It is impossible to make an accurate estimate of the future growth; but consideration should be had of the variable conditions which may enter to change the final result, and the lines laid out in such a way as to make them of the greatest present use, while later they may be extended to meet the future needs. Even at the present time such precautions may be taken in planning extensions to existing lines, and in this way the improvements will be of greater value to the community than if changes are made to meet the present requirements only.

The second important factor in determining the adequacy of a street railway is the use made of it by the public. Again statis-

ties may be employed to show the probable value of a road to a city. The number of rides which each inhabitant is liable to take increases with the size of the place in which the road is located, the growth being very rapid in the smaller towns and much less after a certain size is reached. A curve between the annual number of rides per inhabitant and the size of the city is shown in Fig. 193. This information is valuable in connection with estimates of probable growth in population to prevent making the assump-

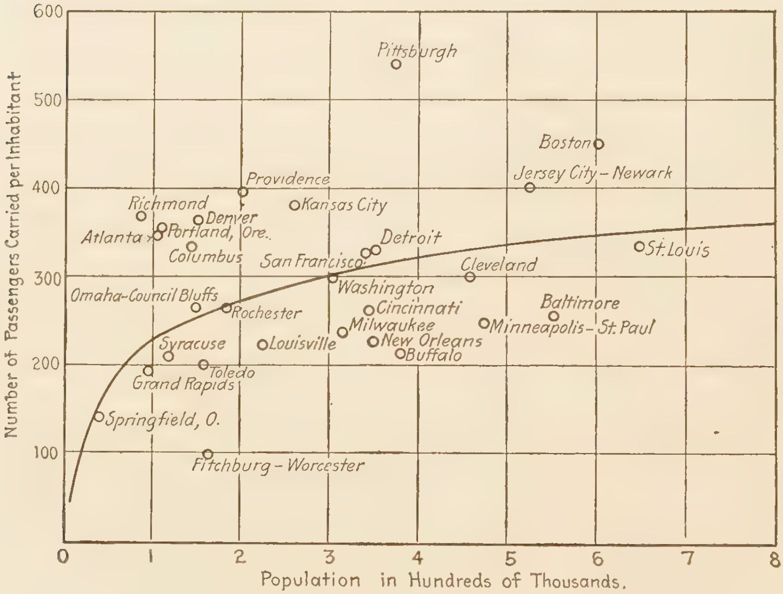

FIG. 193. Relation of rides per inhabitant to population.

tion that the use of the road will increase as a direct function of this gain.

Since the rate of fare in most cities is fixed by law, the values determined above give at once the gross earnings from transportation. The fare on practically all urban lines is five cents, so the number of passengers is a direct measure of the receipts. It should be noted that transfer passengers must be omitted from this estimate, since they do not add anything to the revenue, although it is the usual practice to include them in the total number of passengers carried. On this point there is a great deal of misunderstanding, since many railway officials look on transfers

as an unmitigated evil. This is largely a misapprehension, for the use of transfers often permits the routing of cars to give a much more efficient service than were through routes used exclusively. In such cases the use of transfers is a positive benefit to the company.

Number of Cars.—The number of cars and the frequency with which they are operated are quite difficult to estimate properly. They have a direct effect on the cost of the service and an indirect one on the number of passengers carried. Other things being equal, the number of persons who will ride increases with the frequency of operation up to the point where cars are run every two or three minutes. Beyond this there is no great possibility of obtaining more passengers in this way. The worst feature in modern city operation comes from the excessive congestion of traffic at certain times during the day. By far the greatest number of the regular passengers begin work at approximately the same hour, and stop at the same time. This means that facilities for handling a great number of passengers must be provided, while they are only in use for a few hours, twice a day. Even with the best and most modern equipment, it is hard to provide even standing room for all the passengers, while at other times the cars will be nearly empty. This condition is inherent to American business methods, and can be avoided only by a large amount of educational work. A variation of only a few minutes in the time for closing stores, factories and offices would make a great reduction in the peak of the load, with a corresponding improvement in the service. This point has already been considered in connection with the determination of power requirements.

It is erroneous to suppose that the greatest earnings of the railways come from the crowded cars run during the rush hours. As a matter of fact, the congestion calls for the operation of cars additional to those on the regular schedule. Although these special cars are used but a few hours a day, their first cost, and the cost of the entire system necessary for their operation, is as great as though they were in continuous service. In addition the platform men must be given a living wage, and this must be done even if the amount of time of actual service is but two or three hours a day. It is not often possible to arrange schedules to provide continuous employment for these men.

Size and Type of Cars.—The proper determination of the type of car to use for any urban road is largely a matter of individual

taste. Many kinds are in use on such lines, and the apparent lack of agreement indicates that no single type is entirely satisfactory for all classes of service. It would appear that for street railways in the smaller cities, cars with bodies about 20 ft. in length, mounted on single trucks and equipped with two motors of from 20 to 30 kw. each, will meet the average requirements. Cars of this type will seat about twenty passengers and will provide standing room for as many more. For the larger cities, additional capacity must be provided, which can be done only by the use of units of greater size. This naturally calls for double-truck cars, since a 20-ft. body is about the longest which can be mounted on a single truck, unless some form of non-parallel axle is used. The details of cars for this class of service have been discussed in Chapter VIII.

Schedule and Maximum Speeds.—In many cities, the maximum speed of cars is defined by law. While this has some effect on the schedule speed, it can be offset by the acceleration which is used. It has been shown in previous chapters that the latter has as great an effect on the schedule speed in short runs as does the maximum velocity attained. When a great many stops are made, the schedule speed which can be reached is usually very low, often not more than 10 miles per hr., unless the motor equipment is entirely abnormal. It is advisable not to attempt high speeds under such conditions, since the cost is out of all proportion to the advantage gained.

Where the run includes a certain distance in suburban territory, in which the speed can be materially increased, it is frequently the custom, as has already been mentioned, to use motors for the entire division geared so that the cars may operate at high maximum speeds in the suburban district. The result of this is to overload the motors, while the schedule speed which can be maintained is frequently less than could be reached were the same motors used with a higher gear ratio, giving a lower maximum speed. The most desirable arrangement is to use motors geared for the maximum acceleration, but obtaining the high speeds needed by the use of field control. This will give the advantages of the low and the high gear ratios, and will reduce the power and energy requirements by a marked degree. Tests which have been conducted on such equipments show considerable savings over the normal single-speed motors.

Interurban Roads.—The probable earning power of interurban railways is much more difficult to estimate than for city lines. A great deal depends on the kind of service given and the facilities which are offered farmers residing along the road for light freight service. Generally, high schedule speeds are less important than frequent service, since a large part of the passenger traffic is local.

Since the revenue of the normal interurban railway is so largely from passenger traffic, a careful analysis of the population served, and the number and length of rides per inhabitant, must be made in order to get a close estimate of the probable gross earnings. The factors which enter are so materially different from those which govern the earnings of urban roads that very little aid can be had from a comparison with such properties.

The sources of passenger traffic for interurban roads depend to a large extent on the location of the principal cities along the line. Usually an interurban railway is constructed with one city of considerable size as a primary terminal. The road may operate from this point entirely through rural territory, serving this and the small towns located along the line; or it may connect the principal city with one or more of smaller size. The greatest source of passenger traffic is ordinarily travel from the rural districts to the main terminal; but if the road exceeds a certain length, the traffic from this source will not increase greatly with additional distance. For such roads a second terminal is necessary, and the greater the length of road, the more intermediate cities are essential to give the earnings requisite to make a successful property.

The estimation of the city population served is apparently quite simple; but to obtain figures which have any direct value is much more difficult. The travel which will be obtained between a terminal city and the surrounding territory does not depend to any material extent on the size of the city, but rather on the relations which exist between the urban and the rural populations. For example, a county seat will have considerable traffic *from* the surrounding country, but very little *to* it; while a manufacturing center will probably develop both classes of travel, especially if the territory surrounding it is largely of the same general character.

The estimation of the rural population served by the proposed road is usually made by considering a section of territory from one to four miles wide, on each side of and contiguous to the track. Some objection may be found to this method, in that the amount

of travel to be expected depends perhaps more on the size and character of the towns along the line than on the farming population served by the road. An alternative method is to adopt a factor for use in connection with the population of the intermediate towns located along the line.

A very important consideration is that of the probable future growth of the territory served, and an estimation of the effect this will have on the earnings of the road. A good interurban service does, without question, develop the country through which it passes; but the *amount* of such growth may be a vital factor in determining the success or failure of the property. It is usually impossible to build roads before the population is great enough to allow them to earn operating expenses, although in the past many such lines have been built; but, if the probable increase in revenue due to the presence of the road is sufficient, it may pay to install it before the traffic is enough to pay dividends on the stock. Such a determination is very difficult to make, and great care should be taken to prevent loss of capital. In general, the probable earnings from a projected line are subject to so many variables that the best procedure in such preliminary estimating is to secure the services of the best engineering talent available.

Operating Expenses.—Of equal importance to the expected revenue is the probable expense of operation of the road. The principal items under this classification are maintenance of way, maintenance of equipment, and expenses directly concerned in conducting transportation. Maintenance charges depend to a very considerable extent on the excellence of the construction and the equipment; but if these are assumed to be at least of average quality, the estimation of maintenance costs can be made with a fair degree of accuracy by comparison with existing roads of the same general character.

The cost of conducting transportation is a function of the amount of service given, although not directly dependent on it. The cost of operating a car-mile or a ton-mile depends very largely on the number of such units hauled, although such items as the overhead charges for production of power and platform labor are very nearly constant regardless of the use which is made of the road. If the line is to be successful, the regular schedules must be maintained whether any traffic appears or not; and the cost of hauling empty trains is very nearly as great as when they are loaded to their maximum capacity.

Estimation of Construction Cost.—The estimation of the cost of construction is not difficult, once the components have been correctly determined. Having the power demands, the capacity of the generating and substations may be found at once, the number of units being selected to give the desired subdivision of load, with a proper number of reserve machines. By the application of the principles of transmission and distribution circuits, the proper size of the conductors may be determined.

The methods of estimating the number of cars are various, but if a certain standard of service has been decided on, as, for example, the operation of one train in each direction per hour, the required number may be found at once from an inspection of the graphical time-table. A certain allowance must be made for extra service, for repairs, etc. Generally it is best to purchase at the beginning the minimum number which will give the desired service, and add to them as the traffic develops and the use of additional cars becomes necessary. In this way the latest improvements in design may be taken advantage of.

The methods of estimating the probable amount of power required have been taken up in the preceding chapters. Once the schedule is determined, the proper speed–time curves to give the desired performance may be laid out, and the motors selected to meet this requirement. From the current–time and potential curves, the power demands on the substations and on the generating station may be determined.

The amount of energy needed for the operation of the desired schedule is found at once by an integration of the power–time curve; and if the efficiency of the various elements of the equipment be known, the output of the generators at the bus bars and the quantity of coal to be burned on the grates can be calculated.

The cost of platform labor can be found at once from the number of car-hours operated, if the average wage has been established. Other labor is more difficult to determine, depending as it does on a variety of factors. The number of power-plant operators, repair shop men, and similar employees is largely independent of the size of the road, until it reaches considerable proportions. The office force required to handle the business is quite variable, and depends not so much on the number of units operated as on the individual ideas of the management.

Having determined the various items which enter into the operating cost, the total may now be found as their sum.

Net Receipts.—The difference between the gross receipts and the operating expense gives the net income. If the operating expense is found to be greater than the receipts, the investigation may properly end at this point, unless it is found possible in some way to predict an increase of the one or a reduction in the other. If the estimate indicates a net return, further study will show whether this income is sufficient to pay taxes, fixed charges, and other legitimate overhead costs, and after doing this leave a balance available for dividends. This is, of course, the final measure of success or failure of a road. It is essential that the greatest care be taken to make the preliminary estimate accurate, especially if any doubt exists as to the ability of the projected line to pay dividends; and it is better to leave alone a project rather than run the risk of sustaining material loss.

Steam Road Electrification.—A type of problem which is becoming of increasing importance is the electrification of trunk lines. Such roads are usually old and well-established properties, which have already developed a good traffic. The problem is here much simpler, since the preliminary determinations of traffic and equipment are wholly or partially solved before beginning the estimates.

In many cases, all that is desired is to replace the existing steam locomotives with electric, keeping substantially the same schedules and train weights. This is the simplest statement of the problem, and requires the least preliminary engineering. Once the system for the contact line has been decided on, the size and equipment of the locomotives is comparatively easy to determine, since they will be of the same rating as the steam engines they replace. Having found the locomotive capacity, the motor characteristics must next be selected to give correct operation. The speed–time and power and energy curves may now be drawn, giving the demand on the substations and on the power plant. The equipment for these parts of the system, and for the transmission and distribution circuits, may be selected, and the total operating cost peculiar to the electric installation found.

The criterion of excellence which must be met is that the operating cost of the electric equipment must be less than that for steam, after including a proper allowance for the increased cost of construction. If the total annual cost is less than for steam op-

eration, the project is feasible and may be recommended; otherwise it is necessary to look toward other reasons for the adoption of electricity.

Even though the electric operation of a division may not show a decreased cost directly, there may be other conditions which modify the problem to make electrification desirable. It may be possible to haul trains at a higher speed, thus permitting the passage of a greater number of tons in a given time; or it may be possible to give more frequent passenger service by operating more and lighter trains. Many such considerations must be looked into and may give excellent reasons for electrification, even though the direct saving to be obtained is small.

In some cases, the change from steam to electric operation has caused an increase in passenger receipts. This is sometimes due to the fact that competing lines have been taking a large share of the traffic, which can be regained by better service; and in other cases to an increased desire to travel, on account of the improved accommodations. It is impossible to do more than hint at the possibilities of this sort, and they must be determined for each individual case.

An instance of the successful application of electricity is in mountain-grade operation. Here the limiting conditions usually depend on the weight of trains which can be handled by steam locomotives. Some roads have found the capacity of an entire railway system limited by that of a single short division. If light trains are run, the requirements of safe operation limit materially the capacity of the track; and if long trains are used, the speeds which are feasible with steam are decidedly low. Electric operation makes possible the running of heavy trains at fairly high speeds, so that the number of tons which can be hauled may be materially increased. This is due to the practicability of concentrating larger amounts of power in the equipment than can be done with steam.

Choice of System.—Reference to Chapter XVII will show that of the three systems of secondary distribution, any one will fulfill the requirements of ordinary trunk-line operation. No general agreement has been reached as to the complete superiority of any one; but for a particular installation there may be a solution of the motive-power problem which will be the most satisfactory. If any doubt exists, the best way is to prepare separate estimates based on the use of each of the three systems, obtaining the

relative costs of installation and operation. Except in rare cases, one of them will show a lower total operating cost than either of the others; and, unless there are separate considerations to be met, this is the one which should be adopted.

It would be exceedingly desirable to adopt for an entire railroad system, or for all the railroads of the country, a single universal plan for electrification. This would permit standardization of equipment, and would reduce the cost of the various parts of the electrical apparatus. Until this is done, the cost of installations for electric lines will be considerably higher than if such standardization is brought about. It would be a poor policy, however, to postpone the electrification of such lines as warrant the change until such a condition has been realized; for, with the systems all possessing points of excellence, any one of them may show operating economies which will make the saving sufficient to warrant its adoption, even with the possibility of a future change in case some universal or superior type of equipment is adopted later.

In the final analysis, it may be seen that the use of electric power presupposes a certain traffic density before it becomes a paying investment, so that the lines of heavy travel are certain to be electrified first, except that where coal is expensive and electricity is cheap a comparatively light traffic may make the change desirable. Such conditions exist in the Mountain states, where water power is available; and at the present time at least one important road is equipping its main line for electric operation in the interest of economy, there being no other basic reason for the adoption of electricity. Apart from such special installations, it is quite probable that the Eastern roads will be the first to use electric power for the operation of long divisions, since they are the ones which will receive the greatest benefits from so doing.

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